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REVIEW OF CURRENT RBC PERFORMANCE AND DESIGN PROCEDURES

by

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16. ABSTRACT

The rapid emergence of rotating biological contactor (RBC) technology as an alternative secondary wastewater treatment process has increased the need to review their performance history to provide information to the design engineer. This study, to review and compare current design procedures with field performance, was accomplished by a review of the literature; evaluation of process theory and system characteristics; field survey of plants at or near design flows for process and equipment performance, O&M requirements, and power requirements; and a comparison of design expectations with empirical performance.

Equipment performance, centering on shaft failures and media deterioration, was found to be a problem. Process performance was hampered due to oxygen limitation primarily in the first stage, due to organic overloading. For the range of conditions found at the plants surveyed, process performance did not meet design predictions for percent BOD removal or mass BOD removal.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The purpose of this project was to evaluate the design and performance of rotating biological contactor (RBC) systems. The rapid emergence of RBC systems as a viable secondary treatment process has increased the need for a review of their performance history to provide background for the design engineer. This investigation was designed to partially fulfill this need by evaluating the process performance and operating history of RBC facilities treating municipal wastewater.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

Over the past two decades, rotating biological contactor (RBC) technology has become a viable alternative for secondary wastewater treatment. As of 1979, there were approximately 263 municipal facilities in the United States utilizing RBC's. The focus of this report is to review and compare design procedures currently in practice with field performance of the process. This was accomplished by a review of the literature; an evaluation of process theory and system characteristics; a survey of O&M requirements, equipment performance and power requirements at RBC's operating at or near design conditions; and a comparison of current design guidelines and practice to observed performance.

Sixteen domestic RBC facilities operating at or near design flow conditions supplied monitoring data which were used to evaluate process performance. Design flow-rates in these 16 facilities ranged from 0.2 to 2.8 mgd. The reliability of these plants in meeting effluent concentration criteria or removal efficiency criteria was evaluated. The performance criteria, defined by NPDES, are 30 mg/L BOD and 85 percent BOD removal efficiency, respectively. The results of the evaluation indicated that the plants exceeded effluent criteria 12 percent of the time and failed to meet BOD removal efficiency criteria 67 percent of the time. For the range of conditions found at the plants surveyed, RBC process performance did not meet design predictions for percent BOD removals and mass BOD removal rates.

Equipment performance is a severe problem in existing RBC systems. The nature of the problem centers on shaft failures and media degradation. Of the 17 plants surveyed there were 12 shaft failures reported and the media in three plants had become brittle or failed due to shifting. As a result of this poor operating history it was concluded that design engineers should require an RBC equipment warranty sufficient to protect the owner against equipment failure.

Empirical RBC design approaches were examined relative to more fundamental approaches. Fundamental approaches are useful in identifying the substrate removal and limiting mechanisms, but are difficult to apply to design conditions. A two-stage design approach is presented which first presents design conditions which avoid oxygen limitation and second presents a Monod-based model with the capacity to predict interstage performance. The methodology presented provides a mechanism for bridging the gap between the oversimplified empirical approach and more rational, but complex, fundamental methodologies. Utilizing this interstage design model, an assessment of the benefits of staging surface area distribution and step feeding is discussed.

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SECTION 1

INTRODUCTION

Over the past two decades, rotating biological contactor (RBC) technology has become an alternative to conventional secondary treatment processes in Europe and the United States.

As of 1979 there were approximately 263 RBC installations treating municipal wastewater in the United States. A complete listing of these identified facilities is presented in Appendix A. Table 1 lists the distribution of municipal treatment facilities by flow range. Approximately 25 percent of the existing facilities are package plants (generally less than 0.1 mgd) provided as complete systems by RBC manufacturers. As of 1979, the largest operating RBC facility in the United States is an 80-shaft, 54-mgd facility in Alexandria, Virginia.

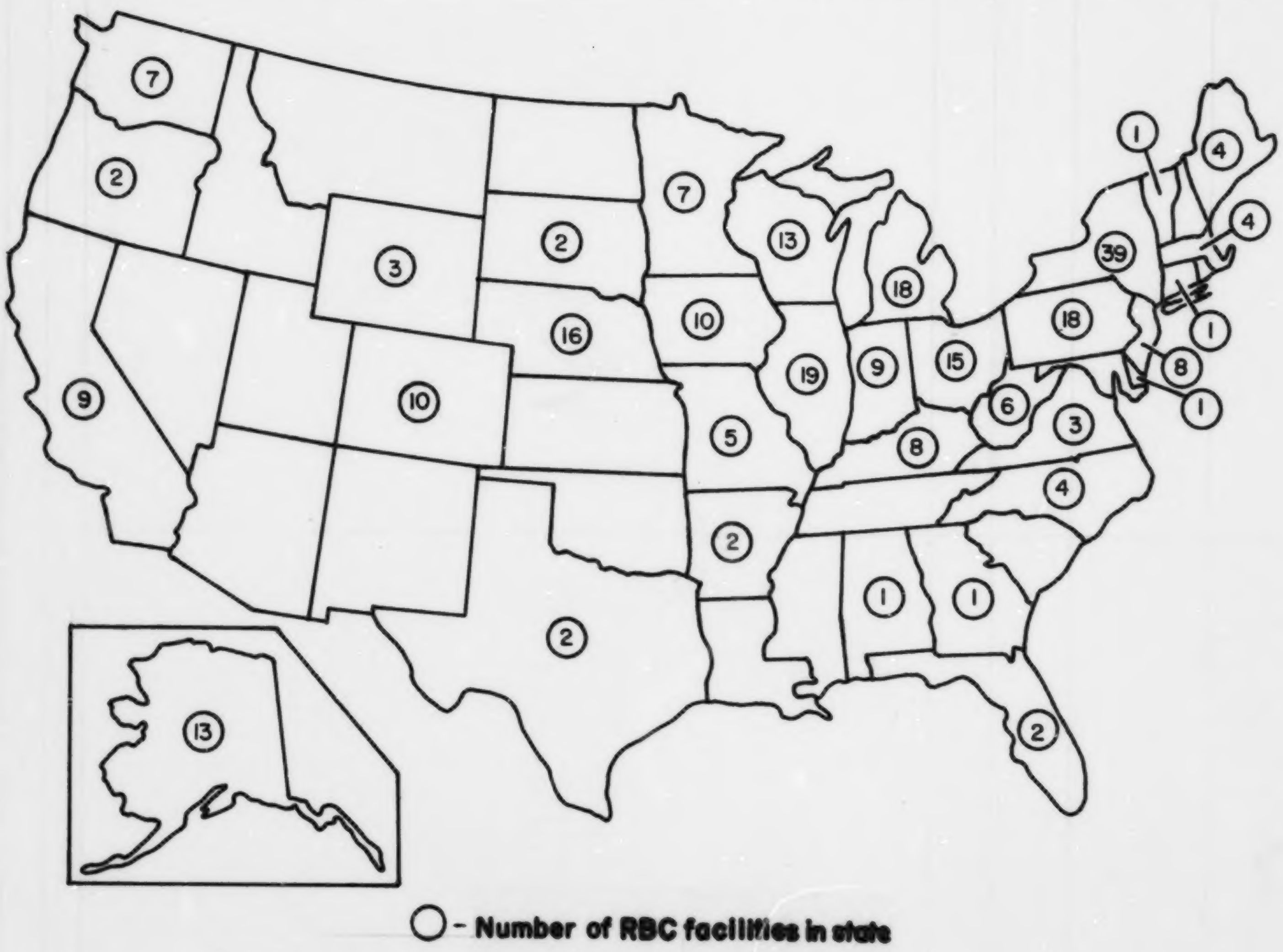
Figure 1 displays the regional distribution of RBC municipal facilities in the United States. The vast majority are located in the northeastern and midwestern portions of the country. New York State has the largest number of facilities, but approximately 80 percent of the 39 identified plants are package plants.

The rapid emergence of RBC systems as a viable secondary treatment process has increased the need for a review of their performance history to provide background for the design engineer concerned with improving the design, operation, and reliability of these systems. This investigation was designed to partially fulfill this need by evaluating the process performance and operating history of RBC facilities treating municipal wastewater and approaching design flow conditions.

The investigation included site visits to a total of six plants to review process performance and 14 plants for power measurements. In addition, process performance data was collected from 16 plants, contacts with operators of 8 additional plants with organic overloading problems were made, as well as contacts with operators of 24 plants to review maintenance requirements. A listing of the plants included in the study and information collected from each are presented in Table 2.

TABLE 1. NUMBER OF OPERATING MUNICIPAL RBC INSTALLATIONS (1979)

Number of installations	Flow range mgd
74	0 - 0.1
57	0.1 - 0.5
41	0.5 - 1.0
74	1.0 - 5.0
8	5.0 - 10.0
5	10.0 - 20.0
4	> 20.0
TOTAL 263	


7
2
9
3
10
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16
7
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5
2
2
13
19
18
9
15
8
6
18
3
4
1
1
2
39
1
4
4
1
8
1
13
○ - Number of RBC facilities in state

Figure 1. Regional distribution of RBC facilities (1979).

TABLE 2. TYPES OF INFORMATION COLLECTED FROM THE RBC FACILITIES SURVEYED

Plant ID No.[1]	Process	Operation & maintenance	Power
1	X	X	
2	X		
3	X		
4	X	X	X
5	X		
6	X	X	X
7	X	X	X
8	X		
9	X	X	
10	X	X	
11	X	X	
12	X	X	
13	X	X	X
14	X	X	
15	X	X	X
16	X	X	X
17		X	X
18		X	X
19		X	X
20		X	X
21		X	X
22		X	X
23		X	X
24		X	X
25		X	X
26		X	X
27		X	
28			
29	X[2]		
30	X[2]		
31	X[2]		
32	X[2]		
33	X[2]		
34	X[2]		
35	X[2]		
36	X[2]		

---

[1] Plants are identified in Appendix D.

[2] Reviewed for organic overloading problems only.

SECTION 2

CONCLUSIONS

PROCESS PERFORMANCE

A survey of 16 RBC facilities (Section 8) with an average influent BOD concentration of 124 mg/L revealed that these plants have greater success in complying with effluent concentration criteria (maximum 30 mg/L) than they have with percent BOD removal standards (85 percent minimum). Average monthly percent BOD removal for the plants surveyed (Figure 12) was 82 percent and varied from 75 to 90 percent for one standard deviation from the mean. The average monthly effluent concentration was 18 mg/L, with one standard deviation from the mean producing a range from 12 to 28 mg/L. Unacceptable performance was traced to either organic overload or underload conditions.

Organically underloaded RBC systems are common in facilities experiencing significant inflow and/or infiltration problems. The high flow rates can dilute the wastewater, resulting in influent concentrations less than 75 mg/L BOD. These low organic concentrations are not readily absorbed and assimilated by the biomass, and result in lower removal rates and reduced efficiencies.

Organically overloaded systems refer to facilities where the influent and reactor organic concentrations result in dissolved oxygen limitations in the initial stages of the RBC system and reduced organic removal rates. In some facilities, the first stage may be organically overloaded, but subsequent stages are capable of increasing their respective organic removal rates in response to the higher influent organic concentrations. The result is that final effluent concentration is still acceptable. In instances where subsequent stages are not available, final effluent quality does not meet secondary treatment requirements.

Of the design loading parameters reviewed (Section 8), a linear regression analysis utilizing mass organic removal versus mass organic loading resulted in a better data correlation than mass organic removal versus hydraulic loading or percent BOD removal versus hydraulic loading. If the design loading parameters divide the data into influent concentration ranges, then a straight line fit is better represented by mass organic removal versus hydraulic loading. Although mass removal design parameters correlate well with field data, they are limited in that small changes in these design parameters can result in significant variations in effluent concentration (Figure 16).

DESIGN PROCEDURES

The majority of municipal wastewater RBC systems are currently designed using manufacturer-derived empirical design relationships which are based on observed municipal wastewater treatment performance. For the range of conditions observed at the 16 RBC plants (described above) cumulative RBC performance in terms of percent BOD removal fell below manufacturers' design procedure recommendations (Figures 17, 18). More fundamental design approaches have been formulated which account for diffusion of oxygen and substrate concentrations; they include various diffusion and substrate uptake coefficients. However, the complexity and lack of calibration for many of these coefficients decrease the applicability of these approaches in municipal wastewater design. Statistical approaches have been proposed which involve multiple regressions analysis; however, they are unproven in applications outside of their initial calibration. Simpler rational design procedures which independently define the effects of oxygen limitations or organic overloading and substrate removal on RBC performance now under development by EPA's Office of Research and Development, will be of greater utility to design engineers.

Dissolved oxygen limiting conditions were observed to be the most significant problem associated with RBC performance. Only one manufacturer (2) currently recommends design modifications which account for dissolved oxygen limitations. This design criterion is defined in terms of limiting lbs BOD/day/1,000 sf. A review of 23 operating RBC facilities revealed that nuisance organism growths associated with dissolved oxygen limiting conditions were reported for facilities with a first stage BOD loading greater than 6.4 lbs/day/1,000 sf (Figure 22).

Utilizing this limitation as an input, a Monod-like model was calibrated (Section 10) at an average influent concentration of approximately 100 mg/L BOD (50 mg/L soluble BOD). This model is capable of predicting interstage performance. However, it was calibrated under a limited range of influent conditions and can only be applied at its calibration conditions. The model presented compared favorable with actual field conditions (Figure 28).

An analysis of interstage performance using this model revealed that less overall surface area is required for RBC systems with an increasing number of stages. The relative benefits of staging differ with required efficiencies. For higher efficiencies, increased stages are more beneficial than for lower efficiencies (Section 10).

Other design considerations which are not sufficiently addressed by manufacturers' process design procedures include the need to ensure proper influent flow distribution to maintain complete mixing within a stage and the need to address potential solids settling problems within the RBC reactors. Potential solids settling problems can result from inadequate pretreatment or improper reactor and/or baffling design.

EQUIPMENT PERFORMANCE

A review of RBC units manufactured in the United States revealed that they are similar in size, shape, and materials of construction and that component failures were endemic to equipment from all suppliers. From a survey of equipment failures at 17 operating RBC plants (Section 8), it was concluded that shaft failures have the most serious impact to operations and were generally a result of overloading. However, the survey revealed radial arms to have the highest rate of equipment failure (30 percent) out of the five main RBC components: shafts, bearings, radial arms, media, and drive systems (Table 13). Equipment performance was judged to be the most severe limitation currently facing RBC systems.

OPERATION AND MAINTENANCE REQUIREMENTS

Costs associated with the operation of RBC units averaged less than costs reported for activated sludge systems and more than those reported for trickling filters. Labor costs to operate and maintain RBC units, including inspection, lubrication and housekeeping, represent 60 percent of the total RBC operation and maintenance costs. Actual RBC maintenance averaged 2.9 hours per week or 2.7 percent of the total plant requirements. These conclusions were drawn from site visits to and other contacts with a total of 22 operating RBC facilities (Section 6), up to 3 mgd and averaging 1.1 mgd. Therefore, cost estimates based on these results should be limited to plants within this flow range.

A review of staffing requirements at the plants surveyed revealed the following:

1. There is no apparent correlation between the number of personnel (person-hours per week) and plant size. Other factors, such as the overall complexity of the plant, the decision to staff the plant for one, two, or three shifts per day, and the level of weekend coverage combined with the size of the plant determine the level of staff required.

2. For the plants surveyed, responses indicated that current facility staffing was adequate for the RBC process, and the level of operator training was above average.

Finally, a comparison between mechanical and air driven facilities was judged to be inadequate due to the dissimilarity of the plants surveyed (e.g., flow, number of shafts, facility operating hours, etc.). Overall, however, the operational advantage of air drive units (less maintenance time due to the reduction in the number of drive units such as motors, reducers, V-belts or drive chains involved for each unit) are offset by the increased operator time required to maintain RBC rotational speeds.

POWER REQUIREMENTS

A review of RBC manufactureres' power studies together with the results of a WESTON field power measurement program (Section 9) resulted in the following conclusions regarding mechanically driven units:

1. The power consumed by a mechanically driven RBC unit is directly related to the surface area of the unit (linear realtionship).

2. The power consumed by a mechanically driven RBC unit has been reported to be proportional to the rotational speed to the third power.

3. Initial RBC stages of mechanically driven RBC units with thick biological growths consume more power than do latter stages with thinner growths.

4. Power consumption reported during manufacturers' clean media tests (Table 16) are significantly lower than power consumed under field conditions, as reported in Section 9.

5. Standard-density media shafts (100,000 square feet) and high-density media shafts (150,000 square feet) driven by mechanical drives at rotational speeds of approximately 1.6 rpm were field-measured to have average power requirements of approximately 2.3 and 3.4 kw per shaft, respectively.

6. Air drive units with combined standard and high density media, rotating at 1.2 rpm were found to average approximately 3.6 kw per 100,000 square feet of surface area (for a combined standard and high-density unit).

SECTION 3

RECOMMENDATIONS

DESIGN PROCEDURES

Empirical methods published by RBC equipment suppliers are almost exclusively used for the design of RBC's for municipal wastewater treatment. It is recommended that RBC designers become familiar with RBC kinetics, reactor design, and system characteristics (Sections 4 and 8) so that they may incorporate alternative equipment layout, flexibility, and quality control in the design and selection of RBC equipment, particularly when using empirical methods. Additional flexibility in RBC process control is required.

Since no single design approach is completely acceptable for predicting RBC performance, the RBC designer should supplement existing methodologies with field visits to similar facilities to define operating problems and design deficiencies.

It is recommended that organic overload be avoided in RBC design by limiting total BOD loading per stage to 6.4 lbs/day/ 1,000 sf. Organic loading should take into account intermittent sidestream loadings, septage loadings, and average hourly peak loadings, as well as the average daily loadings (Section 10). Further research to verify the 6.4 lbs BOD/day/1,000 sf loading limit per stage observed in this report should be undertaken.

Additional work is needed to define interstage RBC performance with respect to both empirical and more rational relationships (Section 10) in systems which are not oxygen limiting. These relationships can be used in conjunction with the maximum organic loading to effectively design RBC systems.

Kinetic models which define RBC performance in terms of fundamental expressions of the factors governing performance afford a means to analyze and compare alternative arrangements and design parameters. It is recommended that additional research be applied to assist in defining the parameters which make up these fundamental relationships.

Additional studies are also needed to evaluate the effects of temperature on RBC performance.

Finally, it is recommended that additional studies be undertaken to assess the effect of secondary clarifier design on RBC performance. Proper secondary clarifier performance is critical to overall RBC system performance.

EQUIPMENT

Based on the review of RBC equipment performance (Section 8), it is recommended that design engineers should seek an RBC equipment warranty of sufficient duration and scope to protect the owner against failure. It is the opinion of the authors that equipment manufacturers are addressing and will eventually solve the equipment problems. However, on the basis of the previous record and the importance of the shaft and media to the RBC process itself, it is necessary for the design engineer to be confident that his process is not severely limited by equipment reliability.

For RBC equipment, location and layout should be designed to facilitate maintenance. For example, walkways to bearings and motors should be provided and this equipment should be mounted on grade; sufficient room for maintenance and repair should be provided around bearings, motors, and controls. Covers or building roofs should be removable to permit damaged RBC units to be removed and replaced.

Preventive maintenance programs recommended by RBC equipment suppliers are considered adequate and should be adhered to.

Diagnostic RBC tests, outlined in Section 6, are useful in understanding the cause or causes of RBC process malfunctions and should be utilized in improving performance.

OPERATION AND MAINTENANCE

Low labor requirements to operate and maintain an RBC system (within the 0 to 3 mgd range surveyed) are its most attractive feature. The lack of large systems (over 10 mgd) and the anticipated economies of scale make it necessary to restrict the findings of this report to plants in the 0 to 3 mgd range.

Supplemental aeration and step-feeding should be considered in existing plants to alleviate dissolved oxygen limiting conditions in lieu of increasing rotational speed to effect the same results.

Load sensors should be installed with RBC units and used by operators to monitor overloading or excessive sloughing conditions.

Finally, shallow RBC tanks with a 4- to 6-in. clearance between the RBC unit and the bottom of the tank should be used to ensure adequate mixing and prevent solids deposition.

POWER

The results of the power tests reported in Section 9 can be used to estimate RBC power requirements. Relationships described in Section 9 between power, speed, and surface area are applicable to mechanical-drive units only. A comprehensive program to vary speed and surface area and define their relationship to power consumption should be undertaken for air-drive RBC units.

SECTION 4

PROCESS THEORY AND SYSTEM CHARACTERISTICS

GENERAL

The RBC process falls into the category of fixed film biological systems. The supporting media in this case are discs arranged on a horizontal shaft which is continuously rotated in a liquid-filled reactor. The hardware to implement the RBC process, along with a brief description of process configurations available, are presented in Section 5.

Substrate utilization in the fixed film processes, such as the RBC system, is not as well understood as in suspended growth processes such as activated sludge. As has been pointed out by numerous investigators (e.g., Williamson and McCarty (3, 4); Grady and Lim (5)) soluble substrate removal from an aqueous phase involves the transport (diffusion) of all metabolic reactants to the reaction site, metabolism by the organisms in support of growth, and transport of metabolic products from the reaction site back to the aqueous and gaseous (air) phases. There are several resistances to transport which are of significance to an understanding of process kinetics for RBC systems. These include:

1. The gas and liquid stagnant films at the gas-liquid interface which control the diffusion of oxygen into water and gaseous metabolic products back to the air.
2. A relatively stagnant liquid film at the water-biofilm interface, controlling diffusion of substrate, oxygen, and metabolic products to and from the liquid phase.
3. Resistance to diffusive transport within the biofilm itself.

In addition to those resistances to physical transport of reactants and metabolic products, there is the metabolic rate of the attached microorganisms themselves which affects overall process kinetics. In the RBC process the media is also alternately exposed to the reactor liquid and the atmosphere. This stagnant liquid film at the gas-liquid interface is, as a result, exposed to the reactor liquid containing both substrate and dissolved oxygen when the media is submerged; and directly to gaseous oxygen in the atmosphere when the media emerges from the reactor liquid. Figure 2 schematically depicts the resistances to diffusive transfer and illustrates the trend in substrate concentrations in an idealized RBC biofilm system.

Figure 2 can be applied to both the submerged and atmospheric cycles of rotation. During the submerged cycle of rotation the substrate concentration in the outer liquid film can be expected to increase and during the atmospheric cycle of rotation the oxygen concentration can be expected to increase. The substrate and oxygen profile can, therefore, be expected to undergo cyclical changes with media rotation.

In the activated sludge process, particularly the completely mixed systems, conditions in the reactor may be considered to be relatively homogeneous. The microorganisms are uniformly dispersed throughout the reactor so that the substrate concentration to which they respond is the same as the bulk concentration in the liquid. Because of the relative ease with which dissolved oxygen concentration and the physical transport of materials to the reaction site may be independently controlled by mechanical means in the activated sludge systems, the principal variable to be analyzed in those systems is the biochemical reaction rate. In fixed film reactors such as the RBC system, however, the necessity for diffusive transport of the substrate (organic matter) and oxygen from the bulk liquid phase into the biofilm creates a condition where the substrate concentration adjacent to the organisms is less than the concentration in the bulk liquid. The analysis and application of kinetic theory is more difficult in RBC's then because of:

1. The more complex heterogeneous nature of the reactor.

2. Separate phase or direct aeration of the liquid film and biomass.

3. The interdependent relationships among the phenomena controlling substrate transport, dissolved oxygen levels, and substrate reaction rates.

4. The influence of speed of rotation on substrate transport and maintenance of dissolved oxygen concentration.

For the purpose of defining removal kinetics and performance of RBC reactors for secondary treatment, municipal wastewater is commonly considered to be adequately characterized by soluble

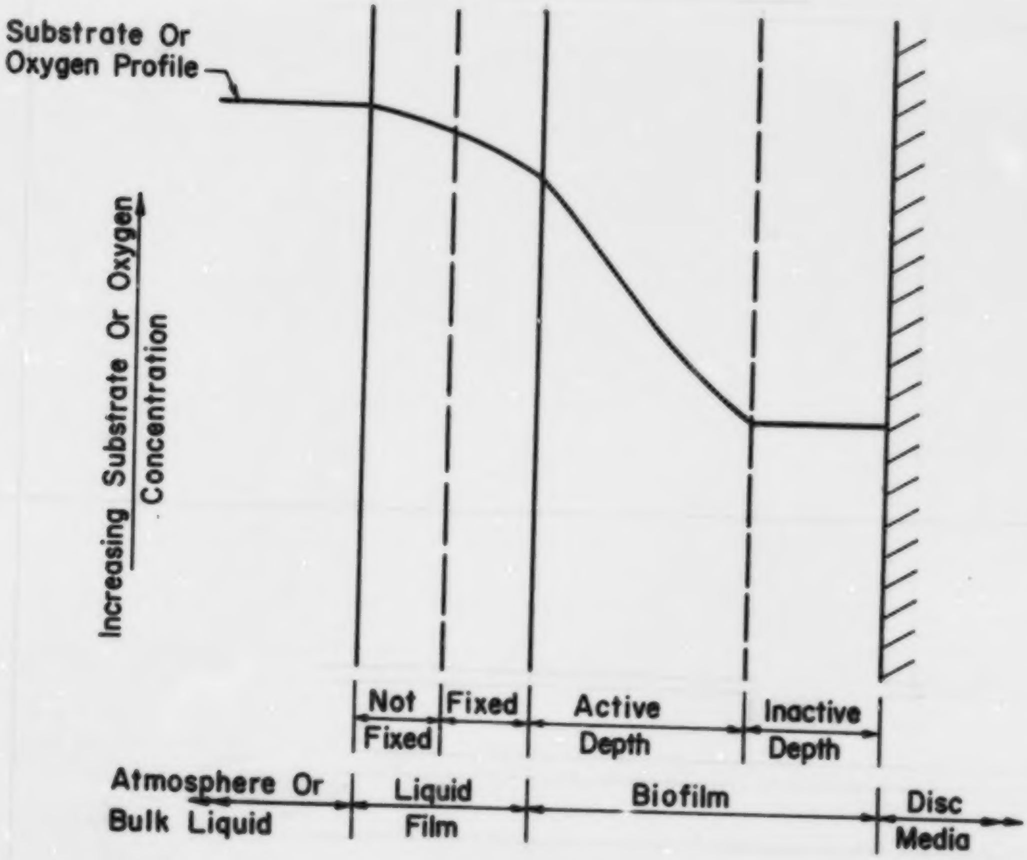
Substrate Or
Oxygen Profile
Increasing Substrate Or Oxygen
Concentration
Not
Fixed
Fixed
Active
Depth
Inactive
Depth
Atmosphere Or
Bulk Liquid
Liquid
Film
Biofilm
Disc
Media

Figure 2. RBC process model for submerged and atmospheric phases of rotation.

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[illegible] EPA [illegible]

②

BOD (SBOD) and by the reaction among SBOD, dissolved oxygen (D.O.), and the microorganisms. The analysis of RBC performance with respect to SBOD removal has been a subject of interest to numerous investigators, as has nitrogen removal. For municipal wastewater there are at least four phenomena that must be described and interrelated in order to describe RBC performance for SBOD removal:

1. Electron donor (substrate) transport.
2. Substrate removal kinetics.
3. Electron acceptor (D.O.) transport.
4. D.O. reaction kinetics.

For each of the components of reaction there can be constructed a transport model and a kinetic model. There are, therefore, at least four expressions that must be developed, one for each component described above. In an overall model describing RBC performance, the expressions must be linked together, as only one of the components will be controlling (or limiting) the overall observed rate of removal at any given time.

KINETIC MODELS

Although the development of a mechanistically sound kinetic model for attached growth systems, such as the RBC, is difficult, several investigators have attempted to describe and relate the fundamental parameters defining the transport and utilization of substrates by attached growths (biofilms). However, few data have been developed to verify the models or to define the range of values of kinetic and transport coefficients as a function of system geometry or operating conditions. There is a definite need for research and development effort to define those values to permit the application of a rational approach to design of RBC systems.

There are several relatively recent theoretical approaches that illustrate the difficulties of constructing a mechanistically sound model for attached growth processes. Williamson and McCarty's model (3, 4) was developed to define substrate utilization within biofilms, considering it to be a process of molecular diffusion with simultaneous biochemical reactions. That model results in an algorithmic solution which balances the surface flux of substrate into the biofilm with the surface flux of substrate that can be assimilated or oxidized within the biofilm. The model requires specification of seven variables including three coefficients: k, K_S, D_W, D_C, X_C, L_1, and L_2, where:

k = maximum rate of substrate utilization, T^{-1}

K_S = half velocity coefficient, ML^{-3}

D_W = diffusion coefficient of substrate in water, $L^2 T^{-1}$

D_C = diffusion coefficient of substrate in film, $L^2 T^{-1}$

X_C = volumetric fixed film biomass concentration, ML^{-3}

L_1 = thickness of stagnant liquid film at biofilm surface, L (reducible by mixing)

L_2 = thickness of liquid film at biofilm surface, L (not reducible by mixing)

While methods were presented for measuring, calculating, or estimating these coefficients, the predicted performance is sensitive to the set of coefficients selected. Unfortunately, many of the coefficients must be estimated, as there is no simple method for direct evaluation. Williamson and McCarty's work, however, does clearly show the effect of the various components of the system on overall performance and draws explicit distinctions between transport of the electron donor and the electron acceptor, and the control of reaction rate by the electron donor or the electron acceptor. While the model has been verified for a specialized experimental device, the model has not been directly applied to RBC's nor has the variation of the model parameters been characterized as a function of the geometry of the system and influent variation.

Also the Williamson and McCarty model can be used only when a single substrate species (either electron donor, e.g., SBOD, or electron acceptor, e.g., oxygen) is limiting with regard to both mass transfer (flux-limiting) and microbial reaction kinetics (substrate-limiting). For most heterotrophic biofilms, such as in RBC's treating municipal wastewater, that is not the case.

Mueller, et al, (6) have described the development of a rational model applicable to the prediction of soluble organic carbon (e.g., SBOD), nitrification, or soluble nitrogen removal. Their model utilizes a modified Gauss-Seidel iteration method to numerically integrate mass balance equations to obtain substrate concentrations in the liquid film, attached biofilm, reactor tank, and liquid effluent from each stage of an RBC system, assumed to consist of flat plates. It is indicated that all mass transfer coefficients are related to system operating conditions and that reaction rates are simultaneously related to electron donor and electron acceptor concentrations. Model calibration runs were made, using pilot plant and full-scale data. Using kinetic rate constants obtained from pilot plant data, the model is described as providing a framework to analyze additional operating modes and conditions, such as the use of air drive instead of mechanical drive, temperature variations, and load fluctuations. As with all models, it is necessary to verify that values of the model coefficients determined in pilot testing and calibration are valid for the extrapolation conditions.

A more detailed analysis for RBC's is that by Grady and Lim (5). Their analysis, which relies heavily on fundamental analysis of hydrodynamic transport, requires specification of some 17 parameters, or coefficients, which allow the analyst to determine which of the four phenomena previously defined are controlling the overall rate of reaction for any particular condition. Based on this analysis, a relationship may be developed which relates effluent substrate concentration as an explicit function of influent flow rate and influent SBOD concentration and an implicit function of the other 15 parameters which may affect performance. It is worth noting that many of these implicit parameters depend on the geometry of the RBC system, its depth of submergence, and its speed of rotation.

The conceptual model proposed by Grady and Lim (5) also incorporates biological kinetics and mass transfer in a relationship to predict performance as a function of parameters characterizing the RBC system. The "effectiveness factor" approach is used in which reaction rate, based on Monod kinetics, is expressed in terms of bulk substrate concentration, and is then corrected for mass transfer effects by multiplying by the overall effectiveness factor. That factor combines individual factors for the submerged and aerated sectors, which in turn includes terms for mass transport to and diffusion within the microbial film. Dimensionless groups (Sherwood number and a modified Thiele modulus) are used to permit determination of an effectiveness factor for a given set of physical conditions. The potential for extension of the model to the situation where there are two limiting substrates (carbon and oxygen) was described, although simulations were not carried out.

Clark, et al, (7) derived a Monod-like expression, $R = PS (K + S)$, by writing a material balance around a completely mixed RBC stage, using Monod growth kinetics and neglecting removal by suspended growth. This expression relates removal per unit area, R, to the maximum areal rate of removal, P, a pseudo-half-velocity coefficient K, and the equilibrium concentration of SBOD in a given stage. Additional discussions and analyses using this model are presented in Section 10.

Other studies to develop models or parameters to define the kinetics of RBC systems have been reported by Pano, et al, (8), Huang (9), and Mikula, et al, (10).

OTHER MODELS

Besides the empirical modeling approaches to design developed by RBC manufacturers, which are discussed in Section 7, several other models have been described in the literature. Several researchers have proposed approaches which utilize multiple regression analyses to develop equations capable of predicting BOD removal. Joost (11) proposed an equation of the form:

$$F = K\, C^{a}\, R^{b}\, T^{c}\, S^{d} \qquad (1)$$

where

a, b, c, d = regression coefficients
K = treatability constant
C = organic concentration, ML^{-3}
R = physical configuration constant, which depends on disc diameter, speed, submergence, spacing, etc.
T = liquid temperature
S = liquid detention time, T
F = percent BOD removal

Antonie and Welch (12), Weng and Molof (13), Poon, et al, (14), and Wu, et al, (15), have all proposed similar regression equations.

In most of the reported data, the models were demonstrated to be useful as predictive models for a given configuration and wastewater. Their utility as design optimization tools is not known.

Eckenfelder and Vandevenne (16) described a model based on multi-zero-order kinetics. Maximum removal was indicated to be defined by oxygen limitation in some cases. Interstage substrate concentration profile data are essential to demonstrate the utility of this approach.

MAJOR SYSTEM CHARACTERISTICS INFLUENCING RBC PERFORMANCE

One of the factors which initially enhanced RBC popularity with the design engineer was the apparent simplicity in the RBC system and what were perceived to be easily definable design factors. Unlike other fixed film and suspended growth biological treatment systems, the RBC has a simple surface area based on the disc diameter and/or surface area configuration; detention times based on reactor volume and wastewater flow rate; and easily controlled disc rotation. Early investigators sought to establish the design of RBC systems based on substrate removal rates per unit surface area at fixed optimal rotational speeds and detention times.

Subsequent investigations, however, have revealed that RBC performance is considerably more complex and is based on numerous factors, some of which are analagous to other biological treatment systems, while others are unique to RBC systems themselves. The major factors influencing performance are shown in Table 3, and are discussed in the following subsections.

Disc Rotation

The rotation of the slime covered discs through wastewater provides both aeration and mixing necessary for effective treatment, as well as the shearing force to remove excess biomass from the rotating disc surface. Disc rotation can be expressed as either tip speed or rotational velocity. Tip speed is related to the disc diameter and rotational velocity by the equation:

$$V = \pi d S \tag{2}$$

where V = tip speed, LT^{-1}

d = disc diameter, L

S = rotational velocity, T^{-1}

All experimental investigations concerned with the effect of tip or rotational speed on RBC performance have reported increased efficiencies with increased speed, up to a limiting or maximum removal rate (17, 18, 19, 20, 21). Initial European investigations (22, 23) recommended maximum tip speeds of approximately 66 ft/min (20 meters/min), based on excessive loss of slime and energy considerations. An EPA-sponsored 5.7 foot diameter pilot plant test conducted by the Autotrol Corporation (20) reported sharp increases in performance up to a limit of approximately 58 ft/min (17.7 meters/min) tip speed, and concluded that this tip speed was the optimum peripheral velocity. On the basis of these early studies, RBC facilities

TABLE 3. MAJOR SYSTEM CHARACTERISTICS INFLUENCING RBC PERFORMANCE

System characteristics	Influence
Disc Rotation	Aeration; mixing; shearing of biomass; power requirements
Dissolved Oxygen	D.O.-limiting condition; nuisance organisms
Flow Rate	Hydraulic loading; organic loading; detention time
Organic Concentration	D.O.-limiting condition; substrate-limiting condition
Biomass Film Thickness	Active depth; D.O. limitation; weight on shaft; power requirements; shaft fatigue stress
Wastewater Temperature	Reaction rate; diffusion rate
Suspended Growth in Reactor	Additional active mass
Staging	Residence time; specialized microbial growths
Influent Load Distribution	Mixing characteristics; reactor concentration; retention time
Disc Diameter	Scale-up factors

in most instances are designed and operated at rotational velocity and tip speeds for standard 12-foot diameter discs of approximately 1.6 rpm and 60 ft/min, respectively.

Although there is consistent agreement throughout the literature concerning the beneficial effects of increased rotational velocity and tip speed, there is some inconsistency regarding the cause of this effect. Early German investigators (22, 23) attributed this increased efficiency to the increased mixing in the liquid reactor and hence improved mass transport. They suggested that any increase in mixed liquor dissolved oxygen due to increased rotational speed was not considered significant, since the microorganisms were capable of receiving a sufficient supply of oxygen to meet their metabolic activities from exposure to the atmosphere during the atmospheric or aeration cycle of rotation. Other investigators, however, have reported decreased efficiencies with mixed liquor dissolved oxygen concentration falling below 1.5 to 2.0 mg/L (17, 18, 24).

In addition to mixing and higher mixed liquor dissolved oxygen concentrations, increased rotational velocities also provide the biomass with greater frequency of contact with the atmosphere and wastewater. This helps to prevent substrate starvation during the aeration cycle (6, 25). Finally, increased rotational velocity provides greater shear forces between the biomass and the wastewater. This can help reduce biofilm thickness, providing a thinner, more active biofilm.

The result of this review is that increased speed is beneficial to RBC performance and benefits substrate removal due to one or more of the aforementioned phenomena. The exact or dominant mechanism is not readily known, but can be assumed to be dependent on the specific rate-limiting condition. For example, under D.O.-limiting conditions, increased mixed liquor D.O. and shearing of the biofilm are probably most significant. Both of these factors will allow for greater penetration of oxygen into the biofilm, reducing or eliminating anaerobic zones and their corresponding problems, as discussed in the next subsection. Under transport-limiting conditions, increased mixing and film starvation are probably most important. Increased mixing and a reduced aeration period would allow for greater substrate concentrations adjacent to the film and increased transport. Disc rotation is limited by physical and power constraints. Excessive rotational velocities would shear all the biomass from the media and power requirements, which are discussed in greater depth in Section 9, increase exponentially with increasing rotational velocities. Practically, RBC rotational velocity is a tradeoff between increased process performance efficiency and power requirements.

Dissolved Oxygen

Previous literature (1, 17, 24, 26, 27, 28) has identified dissolved oxygen as a major performance parameter. Increases in oxygen concentration in the reactor liquid (1, 17, 24, 27) with recommended D.O. concentrations of 1.5 and 2.0 mg/L (17, 24) or in the gaseous phase surrounding the RBC media (26, 28) produced beneficial results. In almost all of the reported investigations the relative benefit of increase in D.O. increased with higher organic loadings.

Dissolved oxygen availability and transfer to the biofilm determines, in great part, RBC process performance. The lack of oxygen in any portion of the biofilm results in a process condition where D.O. transport is the rate controlling factor in RBC performance. This condition results in reduced substrate utilization rates.

Dissolved oxygen deficiencies can result from wastewater with high influent organic concentration or high hydraulic loadings. These conditions have the same effect - an increase in mass organic loading to the fixed film reactor. High hydraulic loadings increase the mass organic loading to the reactor with less liquid retention time for reducing substrate utilization. Increased organic concentration increases biofilm oxygen demand required for substrate utilization resulting in low D.O.

Anaerobic conditions within the biofilm are responsible for the growth of nuisance organisms which competitively colonize the RBC media surface, leading to reduced removal rates, due to their lower metabolic rates. A sulfide-oxidizing filamentous aerobe and microaerophile from the Beggiatoa family has been identified as a common nuisance organism and has become widely associated with this particular problem in RBC systems (29).

This slow-growing population has a smooth, milky white appearance when predominating RBC surfaces. The odor from the film is somewhat septic and unpleasant, and markedly different from the musty smell of a healthy disc culture (30). Since Beggiatoa are microaerophiles, they can exist at low dissolved oxygen concentration. This makes the inner as well as outer layers of biofilm an optimum environment for Beggiatoa propagation at the expense of aerobic organisms which have more favorable metabolic rates for BOD removal.

Recent surveys of RBC facilities (79) for the purpose of reviewing performance by State of Vermont personnel have indicated that *Beggiatoa* growth was observed in facilities which did not appear to be organically overloaded. This raises the question as to whether wastewaters containing sulfide, even with sufficient oxygen available, could stimulate *Beggiatoa* development. Studies of *Beggiatoa* in activated sludge systems (80) have indicated that *Beggiatoa* growth is dependent on the dissolved oxygen concentration in the mixed liquor. *Beggiatoa* growth was only observed at D.O. concentrations less than 0.5 mg/L.

Surveys performed during this investigation revealed *Beggiatoa* growth in systems which were subjected to intermittently high organic loadings resulting from sidestreams or septage input. Additional discussions concerning D.O.-limitations are presented in Section 10.

Flow Rate

Flow to an RBC unit affects unit hydraulic loading, mass organic loading to the biofilm, and detention time of the liquid waste in an RBC reactor or tank. Increasing flows increase both hydraulic loading and organic loading, and decrease the detention time.

RBC performance is commonly expressed relative to the applied hydraulic loading as flow rate per unit disc area (i.e., gallons per day per square foot (gpd/sf)). Reported hydraulic loadings for municipal wastewater design range from less than 1 to approximately 5 gpd/sf (2).

Sufficient detention or reaction time is necessary in any biological reactor for substrate removal. Detention time is a direct function of available liquid volume within the RBC tank and the wastewater flow rate. Earlier studies concerned with RBC system detention time (31) reported optimum values in terms of required volume to surface area ratios. A value of 0.12 gal/sf was reported as a volume-to-surface-area ratio beyond which increased efficiency was not observed. In the range of normal hydraulic loadings this would correspond to approximately 2.9 hours at 1 gpd/sf to 0.6 hours at 5 gpd/sf. Previous experimental work (32) assessing the influence of residence time suggested that RBC performance begins to be significantly impaired at total residence times less than 60 minutes.

Lower hydraulic loadings, which provide higher system detention time and detention time per stage, provide the RBC with more time for substrate utilization, reducing reactor and effluent concentrations to lower levels. The influence of hydraulic loading on RBC performance has been well documented throughout the literature (6, 19, 20, 25). Increases in hydraulic loading reduce RBC substrate removal in the initial stages and increase substrate removal in the latter stages. Increased removal in the latter stages is the result of increased organic concentrations reaching these stages. The effect on effluent concentration is dependent on the ability of the latter stages to remove excess organics which are not being removed in initial stages.

Little data are available concerning the effects of hydraulic peaking on RBC BOD removals. One manufacturer (2) recommended designing for the peak flow if the ratio of peak to average flow exceeds 2.5 or incorporating flow equalization. No data are provided to support this and no information defines whether this peak flow is instantaneous, hourly, or some other peaking duration.

Organic Concentration

Organic concentration within the RBC reactor is a key parameter defining overall process performance. High organic concentration can result in low levels of dissolved oxygen and a substrate removal kinetic limitation; lower organic concentrations can result in substrate transport limitation. Increasing organic concentrations, similar to increasing hydraulic loadings, result in increasing organic loadings. Additional discussions concerning organic loading are presented in Sections 8 and 10.

Organic concentration can be defined in terms of soluble BOD (SBOD) or total BOD.[1] The SBOD fraction of the total BOD is most accessible and most easily degraded by the RBC biomass. RBC process performance, in terms of SBOD concentrations or loadings, is the practice in some design guides (2). However, for municipal wastewaters the soluble fraction can vary, with reported values for raw wastewater ranging from approximately 0.43 to 0.65 and 0.58 to 0.75 for settled wastewaters (33). Unless actual measurements are available, generally applied SBOD values become questionable.

RBC's can be characterized by a series of completely mixed reactors. In such systems, there are two locations - the influent and the effluent - where organic concentrations are normally defined. In a completely mixed system the effluent concentration is equivalent to the bulk concentration in the reactor. This is the concentration which is adjacent to the liquid layer which in turn is adjacent to the biofilm (see Figure 2) and plays a prominent role in defining substrate transport and ultimately substrate utilization.

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[1] Total BOD is referred to in this report as BOD.

Biomass Film Thickness

Film thickness or depth can influence RBC process performance. Thick films contain greater biomass, but also require greater substrate and oxygen penetration to maintain an active aerobic zone. Thick films also increase the total weight of the fixed film on the RBC media accelerating shaft failures due to fatigue and can clog spacings between the media.

Previous investigations (34, 35, 36, 37, 38, 39) concerned with fixed film depths report ranges of active depths from 70 microns to 200 microns, depending on the substrate concentration and the dissolved oxygen gradient between the film and the bulk liquid. In all investigations, maximum removal rates were defined within these ranges of depths; one investigation (37) reported decreased removal per unit depth of growth when the optimum depth was exceeded. This decreasing rate was attributed to anaerobic end products diffusing outwardly and interfering with aerobic activity.

Structurally, RBC systems are designed to support a given weight. Excessive film growth can provide added undesirable loads to a system. Adequate structural strength, rigidity, and drive power must be provided for the biofilm mass anticipated. Surveys conducted in this investigaton and presented in Section 8, relative to RBC equipment performance, reveal that the additional weight is responsible, at least in part, for accelerated shaft failures.

Clogging of open spaces between media can limit portions of the RBC from exposure to oxygen and substrate. This would result in a reduction in effective RBC surface area and reduced performance. Clogging is a particular concern in the internal non-exposed portion of RBC media which does not come into direct contact with the shearing forces of the liquid. The internal media as a result of newer types of RBC corrugated media configurations (2, 49) are exposed to shearing forces generated by wastewater flowing in and out of the media. These shearing forces could be substantially lower than the exteral shearing forces resulting directly from disc rotation. Additional investigations are needed to assess the potential for internal media clogging.

Film thickness and its effect on performance is closely related to the problems of dissolved oxygen-limiting, anaerobic, and nuisance organism conditions. Excessive film growth resulting from organically overloaded discs can induce these conditions.

Wastewater Temperature

The performance of RBC systems is influenced by temperature. Studies on domestic wastewater (20) have indicated that RBC BOD removal performance is unaffected by wastewater temperatures above 55°F. At temperatures below this level the efficiency drops markedly. There is, however, no consistent agreement in the field today concerning the magnitude of performance drop relative to temperature.

Temperature corrections in biological systems are normally defined in terms of the Van't Hoff-Arrhenius relationship:

$$\frac{K_T}{K_{20}} = \Theta^{(T-20)} \qquad (3)$$

where

K_{20} = reaction rate at 20°C (1/T)

K_T = reaction rate at T°C (1/T)

Θ = temperature coefficient

Investigations on small laboratory models using synthetic wastewater reported values of Θ ranging from 1.025 to 1.010 (40); some field studies (33) have reported values of Θ = 1.010. Actual field data, however, are sparse and have not provided adequate verification of these values.

Suspended Growth

Suspended solids will occur naturally in an RBC system as a result of biofilm sloughing. Values reported range up to 300 mg/L, but in most cases have been shown to be less than 100 mg/L (41, 42). The concentrations are dependent on the organic loading and RBC stage. Suspended solids measurement in RBC tanks are subject to wide variations because of the periodic nature of sloughing and difficulties in obtaining representative samples.

Suspended solids in the reactor add to the available active mass of the system, providing additional biomass available for substrate utilization. This premise is the basis of the Surfact Process which combines an activated sludge and an RBC system (43).

An excess of suspended growth, however, can reduce reactor dissolved oxygen concentration and can contribute to anaerobic conditions in the biofilm. Reported values (32) of the mass of fixed biomass solids relative to the normal suspended solids mass indicate that the quantity of active suspended solids under normal conditions is negligible relative to the fixed biomass. A recent study (44) showed that suspended solids can affect kinetic performance, especially at low hydraulic loadings. This can result because the active biological suspended solids are not wasted out of the system at low hydraulic loadings and, therefore, play a role in substrate removal.

Staging

Staging refers to the physical separation of tanks or of sections of RBC media within the same tank by the use of baffles. This may be done to a single shaft, placing bulkheads perpendicular to the shaft or with a multishaft tank where baffles are placed between shafts. One effect of a staged configuration is that each successive stage experiences an organic loading level lower than the previous. In each, a different environment may be established with predominant strains of microorganisms developing in response to that environment.

Early reports (11, 12, 31) highlighting the advantages of RBC systems include the use of staging which permits the development of specialized cultures on the discs and also improves liquid residence time. In chemical reaction kinetic theory, the use and effectiveness of staging is related to the order of reaction kinetics in the RBC tank or reactor and the nature of mixing in the reactor (i.e., completely mixed or plug flow).

If the RBC stages of a system are completely mixed, then a series of stages is more efficient than a single stage of equivalent capacity for first or higher order reaction rates.

There are few data available from structured studies to demonstrate the real effects or benefits of staging on substrate removal efficiency. A recently reported study on both laboratory- and plant-scale made an investigation of the microfauna distribution in various stages of RBC systems (47). One general conclusion from that study was that the number of microfauna types increased (became more heterogenous) with increased degree of treatment (i.e., from first to fourth stage).

Staging should be considered in process design. Staging for higher degrees of treatment, such as nitrification, can provide for better process control by isolating stages so that carbonaceous loadings can be controlled and the development of nitrifying bacteria can be promoted to obtain nitrification. Additional discussions relative to staging are presented in Section 10.

Influent Load Distribution

It is possible to feed wastewater flow into an RBC system in several ways. For a given stage, flow may be directed either parallel to the shaft or perpendicular to the shaft, and for a given system flow may be directed into the first stage, recycled, or step fed.

Parallel flow is often associated with smaller units (up to 2.0 mgd), where baffles are placed perpendicular to the shaft allowing one single shaft to be separated into a number of stages. Flow paths for parallel flow may be split into as many paths as there are shafts or it may be applied to the shafts in series.

With parallel flow, the loading is concentrated at one end of the shaft. These systems act as semi-plug flow systems, and observations and measurements of biofilm growth and dissolved oxygen concentrations, respectively, have resulted in observed film thickness gradients and dissolved oxygen gradients decreasing from the feed end to the effluent end of these reactors (45).

Perpendicular flow results in a flow regime which more closely approximates completely mixed systems. In observed perpendicular flow systems, with single shaft stages, dissolved oxygen concentration and film growth were found to be reasonably uniform (46). As the number of shafts in a given stage increase, complete mixing throughout the reactor is less likely. Observations during this investigation indicate that in systems with more than two shafts per stage, complete mixing assumptions are quesionable.

Recycling or step-feeding RBC systems are alternative methods of influent load distributions which have not normally been utilized in the past. Both represent an alternative method of equalization and distribution of the load to the available surface area within various stages of the system.

Where flow is intermittent, recycling is practiced to provide circulation of the effluent and sloughed solids. Some previous investigations (14) concerned with the influent of recycling have reported benefits associated with recycling; others have reported no noticeable benefit (27).

Recirculation will reduce the organic concentration and can increase the dissolved oxygen concentration of the first stage influent. It will, also, under average influent flow conditions, decrease the detention time of the wastewater in the reactor since the total flow rate through the RBC's will increase relative to the recycle ratio. Recirculation of nitrified effluent may provide an additional oxygen source, in the form of nitrates, which could be released and utilized by the biofilm.

Step-feeding provides the means to decrease the flow reaching the initial stages of the RBC and to distribute the mass organic loadings more evenly to downstream shafts or stages. When compared to straight flow-through systems, step-feeding increased the total detention time of wastewater fed into the initial stages but decreases the total detention time of wastewater fed into the latter stages. Step-feeding may also be used to distribute the inflow more evenly into a multistage reactor providing for more complete mixing.

The evaluation of the potential effectiveness of recirculation or step-feeding requires consideration of stage-wise kinetics. Available models have not specifically addressed the prediction of the effect of recirculation or step-feeding. The fundamental kinetic models discussed previously in this section may be used if properly calibrated. Additional discussions concerning influent load distribution are presented in Section 10.

Disc Diameter and Scale-Up

Early RBC systems and designers ignored the influence of disc diameter on RBC system design, assuming that total disc surface area represented the key design parameter. As a result, early municipal and industrial RBC designers utilized pilot plants consisting of one- to six-foot diameter discs (20). These plants were used to scale directly to 12-foot diameter disc systems based on observed hydraulic loading efficiency relationships per unit disc surface area.

More recent investigations (24, 38) have shown that smaller diameter systems have, in certain cases, greater removal capacities than larger diameter systems when rotated at equivalent tip speeds. These smaller systems exhibit greater removal capacities per unit area under conditions of high organic or hydraulic loading and low dissolved oxygen concentrations. This substrate removal capacity has been attributed to the greater rotational velocity of smaller diameter systems rotating at tip speeds equivalent to larger diameter systems.

To date, although simplified relationships have been reported between the relative performance of small and larger diameter discs (48), no proven method for scale-up from smaller diameter discs to larger diameter discs has been found acceptable. The relationship is a complex function of disc diameter, organic concentration, wastewater flow rate, and rotational speed. The models of Grady and Lim (5) and Mueller, et al, (6) are capable of simulating the influence of disc diameter on performance; however, greater documentation with field and/or experimental data is required. As a result, at the present time the use of pilot plants with disc diameters less than full scale to develop design relationships for full-scale systems can yield a nonconservative design and is not recommended.

SECTION 5

AVAILABLE PROCESS EQUIPMENT

GENERAL DESCRIPTION

The fundamental dimensions of rotating biological disc systems are shaft length and media diameter. Total surface area is a function of these two variables plus disc spacing. In practice, major manufacturers of municipal RBC treatment equipment utilize a basic disc unit comprised of a 27-foot shaft and disc diameters of approximately 11.5 to 12.0 feet. These units can be used in combination (stages) or alone (with the addition of baffles placed perpendicular to the shaft). The 27-foot maximum length is a structural limitation and the 12-foot diameter is a result of transportation considerations which limit road vehicles to a 14-foot height. Most manufacturers offer a range of shaft lengths from 6.6 feet to 27.0 feet.

All rotating biological contactors produced in the United States today are circular. A number of Japanese manufacturers are offering a hexagonal shaped disc. The differences may have some bearing on manufacturing techniques; however, the requirements for a uniform, balanced load suggests a circular or near circular shape is best.

Materials

Materials used in the construction of rotating biological contactors vary slightly from manufacturer to manufacturer. Disc manufacturers do not directly supply auxiliary equipment such as covers and tanks, but specify their materials and construction to ensure equipment compatibility.

Shaft --

Wall thickness is a nominal 3/4 inch. For higher strength wastewaters, some suppliers will provide a shaft with a thickness of 1-1/2 inches. Steel used must generally meet the strength requirements of ASTM 36, except for the end bearing points which use a stronger material. Shaft cross-sectional shapes vary from circular to square to octagonal.

Media --
Most plastic media is formed from high density polyethylene. Some suppliers use a small percentage of carbon black to retard ultraviolet degradation of the media.

Support --
Systems using structural supports fabricate them from either coated steel tubing or stainless steel structural members.

Tanks --
Most tanks are reinforced concrete structures which are poured in place. Floors and walls are generally 12.0 inches thick. Package plants are fitted into steel tanks with a nominal wall thickness of 1/4 inch. The steel tanks are usually coated with an epoxy material to prevent corrosion.

Enclosures --
To prevent exposure of operating RBC's to sunlight or inclement weather, either prefabricated fiberglass covers or concrete block buildings with steel truss roofs are provided. The advantages presented by using covers includes ease of installation and lack of required maintenance. On the other hand, housing RBC units in a building provides an operator with an immediate view of biological conditions (i.e., nuisance organism growths or excess sloughing) and mechanical operations. Maintenance of bearings and motors is easier when they are located in a building. Buildings are a disadvantage, however, in that the corrosive atmosphere around RBC units requires resistant building materials and accelerated maintenance. In cold climates, buildings must be heated to reduce humidity and ventilated. Covers appear to be the more popular selection by designers because of the reduced cost.

DISC CONSTRUCTION

Disc media is constructed by extruding high density polyethylene into individual sheets which are subsequently formed into the desired surface configuration. Surface configurations are unique to each manufacturer and affect the surface area, turbulence and flow patterns of the liquid over the media. These individual sheets are cut into pie shaped segments, each representing one-eighth the area of the total circular disc.

Some manufacturers group the pie shaped slices together to form a wedge of media (Figure 3). The wedges are supported by steel arms radiating from the shaft and are connected to these arms either by rods penetrating the wedge or by straps holding the wedge. The system rotates by the transmission of torque from the shaft to the radial arms and the media.

< Fig 3

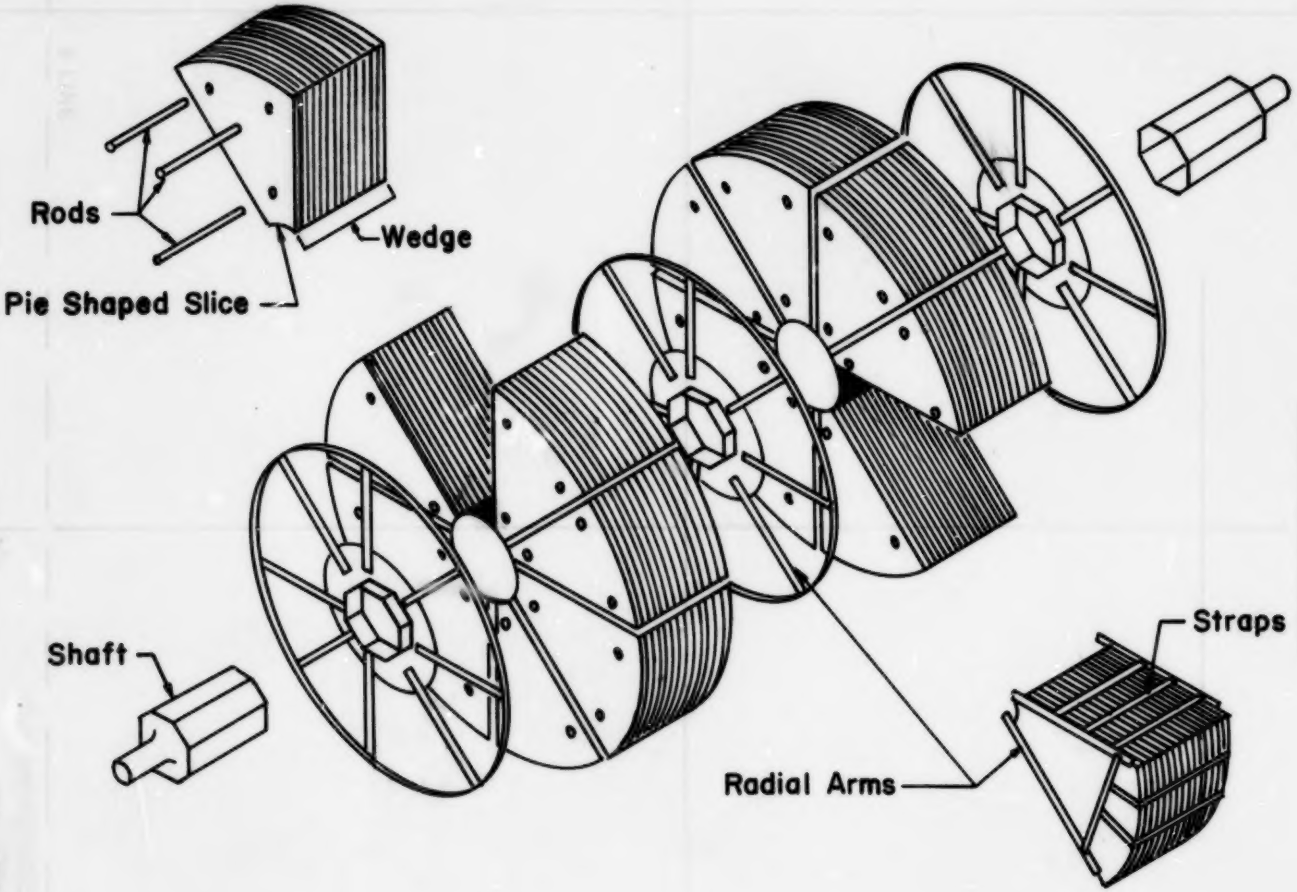

Rods
Wedge
Pie Shaped Slice
Shaft
Straps
Radial Arms

Figure 3. Segmented RBC unit.

③

A second method of construction is a unitized self-supporting plastic disc, mounted on and driven by a square shaft (Figure 4). In this case, the pie-shaped pieces are connected to form circular plates that are, in turn, welded to each other and mounted on the shaft. A reinforced plastic hub provides the transfer of drive from the shaft to the media.

Fig
4

The segmented system enables the media to be replaced without removing the shaft. It can also be an advantage in transportation, since the unit will break down into smaller components. Earlier designs of this type had some problems with movement of the media and subsequent damage, as the wedges responded to the alternating forces of gravity and buoyancy. More recent designs (since 1979) have reduced movement by tightening the media strap supports or by designing for increased stresses at the interface of the media and the support rods. No shifting of the media is possible with unitized construction, but replacement requires that the shaft be lifted.

A third form of disc geometry consists of 35-inch wide strips of high-density polyethylene which are vacuum formed, spirally wound, and heat welded in a continuous wrapping process on a 30-inch diameter circular shaft. Up to eight of these spiral strips can be mounted on a single shaft, producing a cylindrical disc unit with overall dimensions and surface areas comparable to the flat plate RBC's previously discussed.

SURFACE AREA

Media surface area is a function of both disc surface configuration and sheet spacing. Manufacturers generally separate their media into two types - standard media and high density media. For standard media, manufacturers report an available surface area for a 25-foot single-stage shaft between 100,000 and 104,000 square feet for 12-foot diameter discs. High density media, which decreases spacing between individual polyethylene sheets, can increase surface area up to 50 percent, yielding effective surface areas of 150,000 to 156,000 square feet for a 25-foot shaft. The reduction in void spacing limits the use of high density to applications where thin biomass growths can be expected.

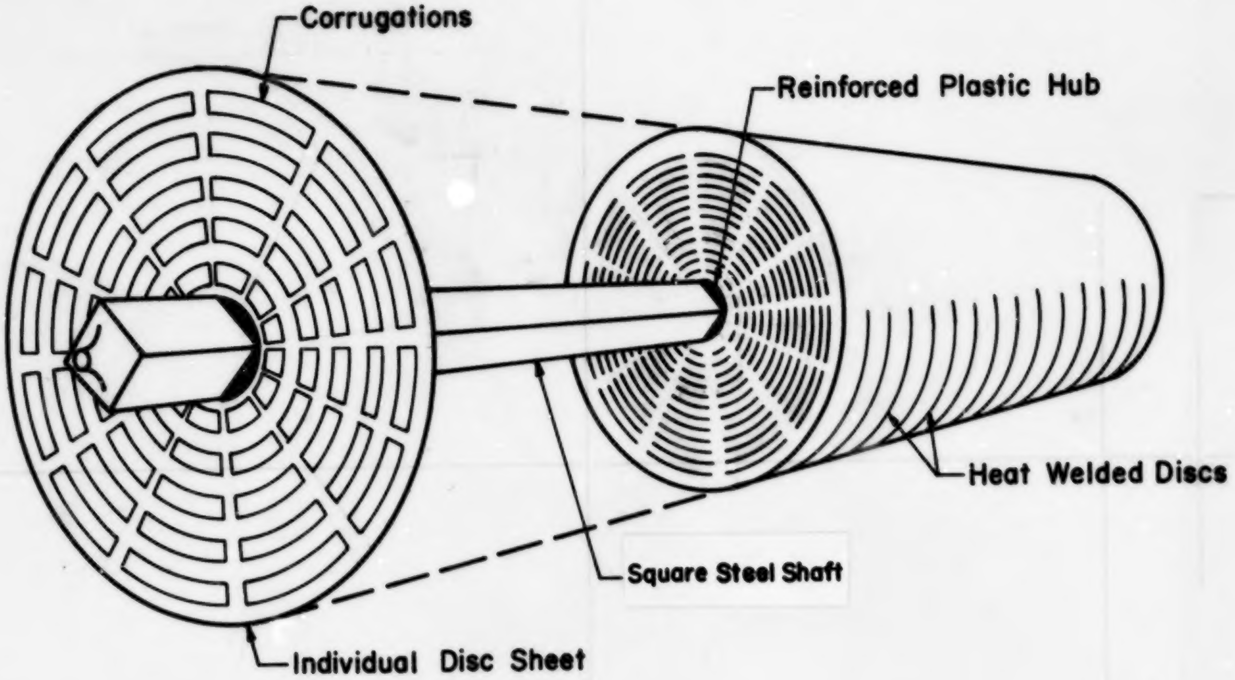

Corrugations
Reinforced Plastic Hub
Heat Welded Discs
Square Steel Shaft
Individual Disc Sheet

Figure 4. Unitized RBC disc construction.

ALTERNATIVE SHAFT LAYOUTS

Number and Length

The number of shafts for a given system depends on the required surface area. Generally the fewer shafts in a system, the lower the capital and operating costs. It is, therefore, common practice to use a 25-foot shaft (largest shaft available) whenever possible.

Staging

Staging refers to the physical separation of RBC media within the same tank by the use of baffles. This may be done to a single shaft placing bulkheads perpendicular to the shaft (Figure 5) or with a multishaft tank where baffles are placed between shafts (Figure 6). The effect of this configuration is that each subsequent stage has a lower organic load than the previous. In each, a different environment may be established, with strains of microorganisms developing in response to that environment (see Section 4).

Flow Paths

Flow is directed either perpendicular or parallel to the RBC shaft. Parallel flow is often associated with smaller units (up to 2.0 mgd). This permits the placement of baffles perpendicular to the shaft allowing one single shaft to be separated into a number of stages. When an entire shaft can be segregated as a single stage, flow is usually directed perpendicular to the shaft. With this configuration three, four, or more shafts can be placed in the same tank and removable baffles used to establish stages. Flow can be split, applying equal parts to each separate RBC unit, or it can be applied in series to consecutive shafts. Figure 7 depicts commonly used flow path and shaft configurations. Many other combinations are possible.

ROTATIONAL SPEED FLEXIBILITY

Rotation of the media is designed to provide:

1. Biomass sloughing.
2. Wastewater aeration.
3. Contact between wastewater and fixed film.
4. Mixing within the reactor.
5. Aeration of the fixed film.

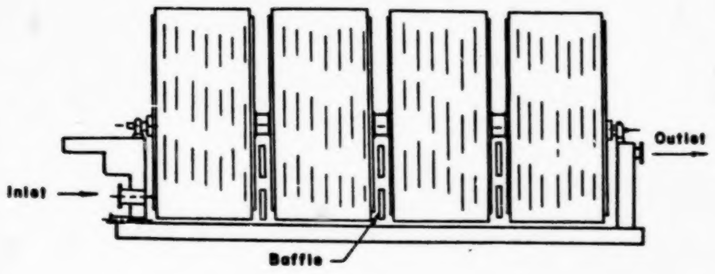

Inlet
Outlet
Baffle

Figure 5. Single shaft staging.

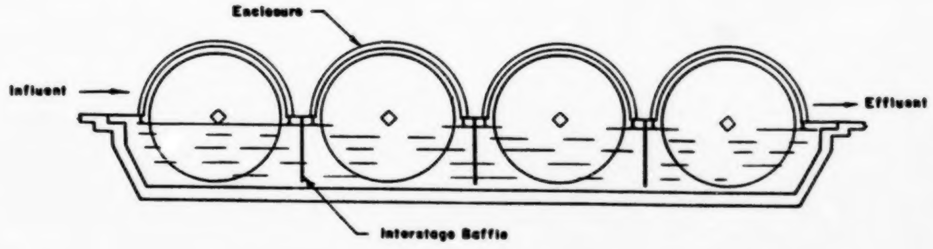
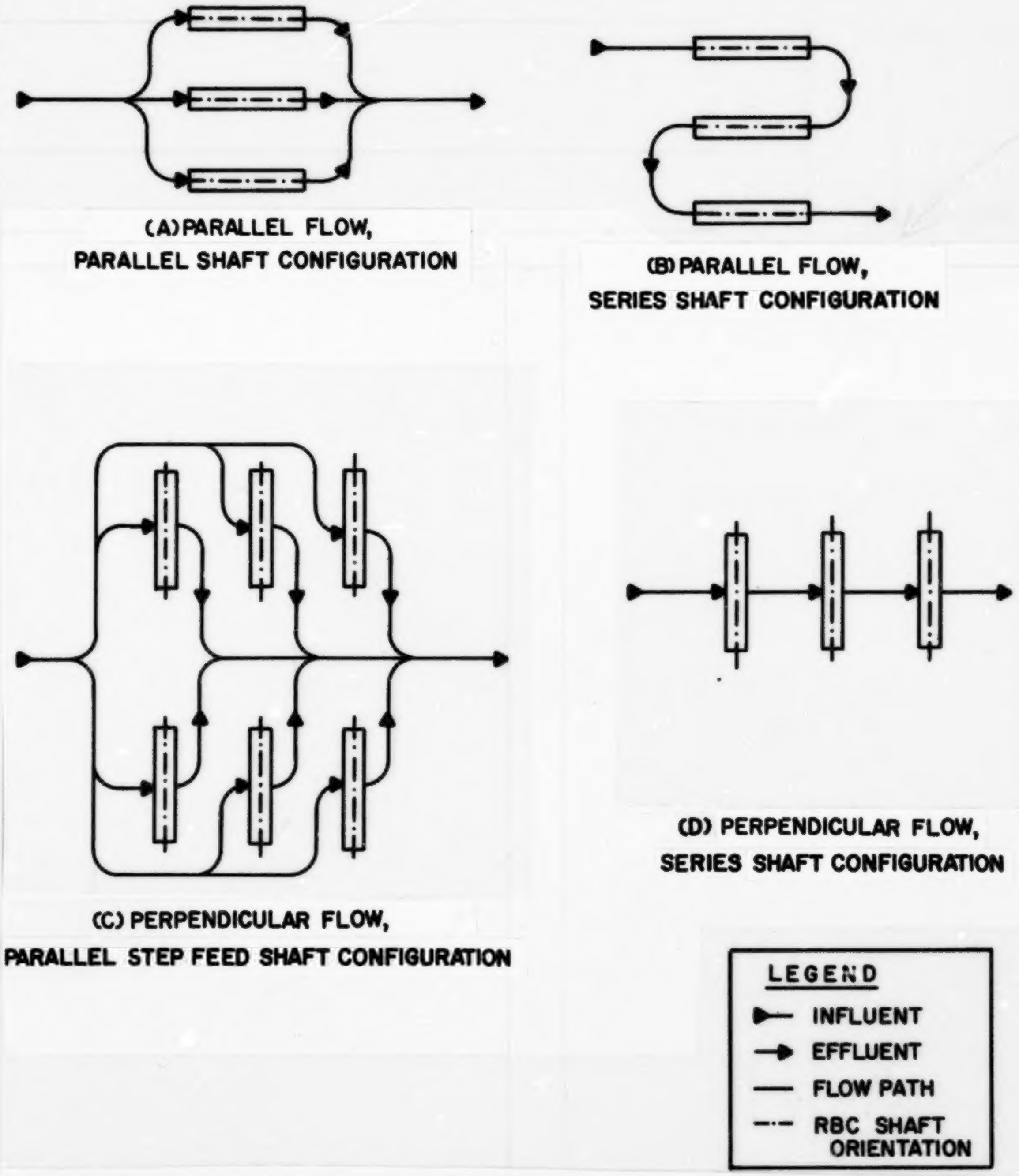

Enclosure
Influent
Effluent
Interstage Baffle

Figure 6. Multi-shaft staging.



(A) PARALLEL FLOW, PARALLEL SHAFT CONFIGURATION

(B) PARALLEL FLOW, SERIES SHAFT CONFIGURATION

(C) PERPENDICULAR FLOW, PARALLEL STEP FEED SHAFT CONFIGURATION

(D) PERPENDICULAR FLOW, SERIES SHAFT CONFIGURATION

LEGEND
INFLUENT
EFFLUENT
FLOW PATH
RBC SHAFT ORIENTATION

Figure 7. Flow path configurations and staging arrangements.

EPA spec

⑥

Some manufacturers (2, 49) recommend different directions of rotation when flow is applied perpendicular to the shaft. When tank depths are shallow (4 to 6 inch clearance between tip of RBC and tank bottom), mixing is considered adequate and short-circuiting avoided with either rotational mode.

In treating municipal wastewater, the recommended peripheral velocity is 60 feet/minute, which translates to a rotational speed of 1.6 rpm for a 12-foot disc.

For mechanically driven units, variation in rotational speeds can be achieved by either use of variable speed drive units or by an adjustment in gearing ratios. Air driven units can increase disc speed with an increase in air flow, but at the expense of higher power requirements. Increasing the rotational speed of mechanically driven units to increase aeration has not become common practice for a number of reasons.

1. As discussed in Section 9, the practice would increase power use exponentially, since power has been shown to vary with the cube of rotational velocity (50).
2. Increased strain on shafts, media, and media supports will occur, and the rate of shaft and media failures due to fatigue, already a problem, can be expected to increase.
3. Subject to a cost-effective analysis, providing increased aeration would probably be better served by a supplementary system of diffused air in the RBC tanks than by increasing the reaeration abilities of a disc unit.

DRIVE SHAFT OPERATION

Bearings

Bearings are one of the components of a disc unit requiring maintenance. Earlier designs experienced deflections of longer shafts causing unequal wearing of the shaft ends and bearings. The use of self-aligning spherical roller bearing units appears to have eliminated this condition. Protection from corrosive wastewater by the use of high moisture bearings and cover plates (idle-end) has reduced another potential problem.

Drive System Components

All mechanical drive RBC manufacturers specify factory-assembled units including motors, speed reducers, and drive systems. Gear reduction systems are either cartridge type units, multi-V-belt, or chain and sprocket systems. The latter two are susceptible to alignment problems, but those in operation have been relatively trouble free. The cartridge type units are gaining in use because of their efficient energy transfer abilities, low maintenance requirements, and ease of installation and replacement.

Motors, Air Compressors, and Electrical Controls

Motors are 3-phase, 60-hertz units. The maximum nameplate rating identified was 7-1/2 hp for mechanically driven units, and 75 hp for air drive plants. Most specifications for mechanically driven units call for an open, drip-proof enclosure with a normal starting torque characteristic meeting the requirements for NEMA Design B. Compressed air equipment for air drive units is not supplied by RBC manufacturers. Their design follows the same requirements used for activated sludge equipment. Typically, on-off motor controls are used for mechanical drive equipment; however, they provide little operational flexibility to the RBC process. Because of power consumption, variable speed motors and controls, though available, have not become common design practice.

LOAD SENSORS

Load sensors are placed between RBC shaft bearings and support points, and monitor the total weight of a disc unit (shaft, media, and biomass). Unusual weight increases reflect increased film thickness, usually the result of higher organic loads. Operator responses might include step-feeding, aeration, or increased disc speed, if this flexibility has been included in the design of the plant. Weight losses mean excessive sloughing, alerting the operator to possible toxic conditions.

AIR DRIVE

Air drive systems use compressed air dispersed from headers located under the discs to achieve rotation. The air is caught in cups attached to the edge of a disc structure. Installation is the same as a conventional unit, but without a motor and drive system. The header is placed below the media as shown in the end view in Figure 8. Air is released at a low pressure (3 psig) into the cups, creating a buoyant force that causes the discs to turn. Some of the air is allowed to enter the space between the corrugated discs, increasing turbulence and dissolved oxygen to the liquid film adjacent to the biomass. If effective, the system would provide two process benefits - thinner biomass, thereby avoiding anaerobic culture development, and provision for increased D.O., an advantage with organic overloads and/or septic conditions. An inherent problem with air drive units is

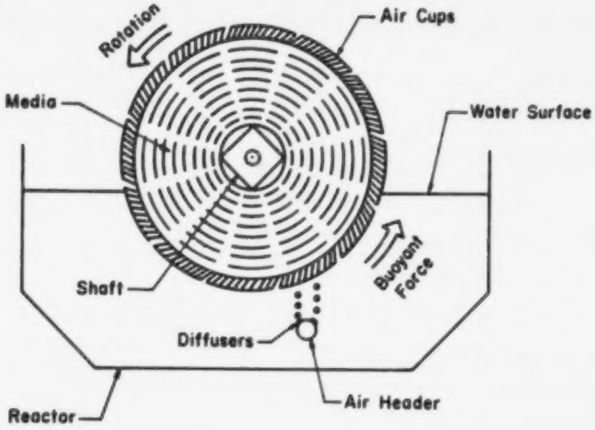


Figure 8. Air drive - end view.

the lack of positive rotational velocity control; an increase (or decrease) in air supply to one RBC shaft causes a change in air supply (and speed) to the remaining units, because provisions are not made to control the air flow to each shaft.

Motor units range from 15 hp for a two-shaft operation to 75 hp for eight shafts. Common designs call for two or three motor/ blower combinations, with one of these units used as an auxiliary. The blower compresses air to about 3 psi. Air is conveyed to the discs by the same type of header/coarse bubble diffuser system found in activated sludge facilities. The manufacturer (2) recommends a peak supply per shaft of 250 cfm, an operating range of 50 to 200 cfm, and an average delivery of 150 cfm. This is considered satisfactory to provide rotational speeds up to 1.6 rpm. Normal operating conditions for these units were found to be 1.2 rpm (51).

SECTION 6

OPERATION AND MAINTENANCE

INTRODUCTION

A review of operation and maintenance requirements through site visits to 20 RBC facilities and phone contacts to two others was undertaken to determine typical O&M requirements at these facilities. As presented in Section 1, RBC installations between 0 and 5 mgd comprise 94 percent of the total operating municipal facilities. Treatment plants with less than 1.0 mgd design flow comprise 65 percent of the total. The facilities examined in this investigation reflect these proportions. The average flow was 1.1 mgd (standard deviation = 0.7 mgd) for the 22 plants from which O&M data were obtained. All of the facilities reviewed fell within a flow range of 0 to 3 mgd and contained less than 12 shafts. Additionally, 59 percent had a design flow of less than 1 mgd. Conclusions drawn from this study concerning the O&M requirements of RBC facilities are limited to plants with hydraulic capacities from 0 to 3 mgd which comprise the vast majority of RBC facilities.

Following some of the earlier visits, it was apparent that detailed O&M costs were typically not available. This was attributed to the small size of the operating RBC facilities in which budgeting and accounting records were not as thoroughly documented or were included in over-all department budgets (such as Public Works), making data collection more difficult and time-consuming, and beyond the scope of the project.

OPERATION AND MAINTENANCE

Cost Data

Annual operation and maintenance cost information was difficult to obtain from the facilities where performance data were collected. Of the 22 facilities studied, two plants (plants No. 13 and No. 15) supplied sufficient cost information to perform comparative analysis. Plants No. 13 and No. 15 had daily flows of 1.0 and 2.0 mgd, respectively. These plants were considered as "typical" RBC facilities and fairly representative of the survey distsribution based on previous experience (i.e., secondary treatment standards).

The average O&M costs for the facilities were compared to to the national average O&M costs for various treatment levels by operational capacity from a previous EPA study (73). All costs were upgraded to the November 1981 ENR index and are compared in Table 4. There is a significant difference in the size of the sampled population for RBC's (n = 2) versus the other processes, so the validity of the apparent cost/size relationship is questionable. Neverless, the O&M costs for the RBC facility operating near design capacity falls between the O&M costs for trickling filter and activated sludge processes. It should be noted that plant No. 13 is operating at less than design capacity (80 percent) and has a lower O&M cost than RBC plants treating wastes at design flows. This is not the case for other processes surveyed by EPA and reported in Table 4 in which plants that are operating at less than design capacity (<90 percent) have higher O&M costs than similar plants treating wastes at 90 to 110 percent of design flows.

Additionally, personnel costs (i.e., labor wages, salaries, and benefits) were observed to comprise approximately 60 percent of the RBC facility expenditures reported in the questionnaires. This agrees closely with a previous EPA study which reported the personnel costs represent 52 and 58 percent of the total O&M costs for activated sludge and trickling filter plants, respectively. Power requirements of RBC's are discussed in depth in Section 9.

Staffing Requirements

The principal factors which determine the organization and personnel required in a wastewater treatment plant are the complexity of the process, the size of the system, and the volume of wastewater that is to be treated. Additionally, the decision to staff the plant for one, two, or three shifts per day, as well as the level of weekend coverage, will affect staffing needs. Higher levels of treatment require more staff because this requirement entails more laboratory work, greater operational manipulation, and additional maintenance requirements.

The number and diversity of job types required to operate and maintain an RBC facility are related to plant size, the degree of treatment, and other unit processes included in the treatment system such as type of solids stabilization and disposal, and chemical feed facilities.

TABLE 4. EPA SURVEY, AVERAGE O&M COST FOR VARIOUS TREATMENT LEVELS BY OPERATIONAL CAPACITY (DOLLARS PER MILLION GALLONS TREATED PER YEAR)[1]

Actual flow as percent of design flow	Level of treatment			
		Secondary		
	Primary	Trickling filter	Activated sludge	RBC
At Design (90-110%)	175	227	256	254[2]
Underload at:				
70-89%	178	235	264	218[3]
50-69%	176	246	420	---
<50%	375	557	582	---

[1] November 1981 ENR (3705).

[2] Plant No. 15.

[3] Plant No. 13.

The facilities visited, listed in Table 5, were limited to small installations with an average flow of 1.1 mgd. Plant operating personnel were categorized into one of the following functional classes: management, operations, maintenance, and other (laborer). Only in-plant personnel were considered. In many of the small plants, these functions were performed by the same person. Supervisory personnel were involved in routine daily operations such as sample collection and laboratory analysis, and plant operators were involved in routine maintenance procedures. This overlapping of responsibilities is not uncommon for small size facilities, and was practiced to varying degrees in all the facilities visited.

For each of the 20 facilities surveyed, Table 5 presents the number and classification of personnel. Correlation between plant flow rate and staff size was poor (r = 0.49) and is attributed to the decision of some plants to provide staff coverage for more than 8 hours per day, 5 days per week. For example, plant No. 24, which had a flow of 0.2 mgd, provided staffing for 16 hours per day plus 8 hours per day on weekends, while plant No. 15, which has a flow of 1.7 mgd, provided staffing for only 8 hours per day. Although the plant flows were substantially different at these two plants, staffing totals were the same.

Plants No. 4 and No. 7 were operated by a private firm whose other clients included approximately 20 other municipal and industrial treatment plants. This mode of contract operations reduced total supervisory and operating personnel on a per-plant basis, while still resulting in well-operated plants (average BOD removal was greater than 95 percent).

Plant No. 25, which has a flow of 0.35 mgd, was staffed by only one operator 8 hours per day, 5 days per week. This facility was managed in conjunction with a larger treatment facility which performed the maintenance tasks at the plant. The operator's main function was to monitor plant process performance.

In-plant personnel requirements at plant Nos. 1, 7, and 16 also included collection system and pump station maintenance as part of the plant operator's responsibilities, which is not a direct staffing requirement for RBC processes. In the other facilities surveyed, collection system responsibility was delegated to a separate department in the Public Works administration.

Five plants (plant Nos. 15, 16, 17, 18, and 26) reported no job classification for operators. In this case, there was a full-time superintendent who directed maintenance personnel or laborers for plant operation.

TABLE 5. RBC STAFFING PROVIDED FOR OPERATIONS AND MAINTENANCE

Plant ID No.	Flow mgd	Number of people assigned per week (40 hr/wk)				
		Superintendent	Operations	Maintenance	Laborer	Total
1	1.9	1	2	---	(5)	8
4	0.07	0.25	1	---	---	1.25
6	---	1	1	---	---	2
7	1.2	0.33	1	(4)	---	5.33
9	0.9	0.5	2	---	1	3.5
11	0.65	0.75	2.25	---	---	3
12	1.4	1	1	---	3	5
13	0.6	0.5	3	---	---	3.5
14	1.3	1	4	---	---	5
15	2.7	1	---	---	4	5
16	0.35	1	---	(2)	---	3
17	0.9	1	---	---	4	5
18	2.7	1	---	---	2	3
21	0.35	1	1	---	---	2
22	0.75	1	1	---	---	2
24	0.2	1	3	---	---	4
25	0.35	---	1	---	---	1
26	0.06	1	---	---	---	1
27	0.4	1	1	---	1	3
28	0.6	0.06	0.25	---	0.75	1.06

( ) includes collection system responsibilities.

All plants surveyed responded that current facility staffing was adequate for the RBC process and the level of operator training was above average (intermediate to advanced level), with many operators being certified. In seven facilities there was only part-time supervisory/management personnel at the plant.

In summary, for the RBC plants surveyed ranging in size from 0.07 mgd to 2.7 mgd, the plants were staffed by one full-time operator assisted by a laborer, with part-time supervisory direction.

Maintenance Requirements

Current equipment maintenance requirements and practices are defined by the equipment manufacturers. Table 6 presents a summary of manufacturers' suggested practices and schedules. All 22 plants surveyed in this investigation follow a schedule of equipment maintenance outlined by manufacturers' specifications or the plant operation and maintenance manual. Manufacturers' equipment preventive maintenance recommendations were judged adequate. Equipment failures to be discussed in Section 9 were due to defects in the original equipment, and were not related to the preventive maintenance program.

Table 7 represents a survey of facility estimates of equipment maintenance requirements. Bearing maintenance (greasing) is the most time consuming of the periodic RBC maintenance requirements. Remote systems or spring loaded grease packs in use at some plants can reduce this time requirement. Plant layout should also facilitate maintenance work; bearings and shafts should be mounted on grade with access paths. Proper layouts and equipment selection can reduce maintenance from a daily to a weekly task.

From the survey of RBC facilities, the relative O&M effort required by the RBC unit with respect to the total facility staff was defined. Table 8 presents the results on a person-hour per week basis. The labor effort was divided into three categories: supervision, operation, and other (laborer category). From the data presented in Table 8 it can be seen that, as a percentage of total plant labor requirements, the RBC portion requires minimal attention. Plant No. 1 had the highest labor requirement, 6.5 percent of total plant O&M; however, the facility has 10 mechanically driven shafts, one of the largest in the survey. This facility has older type bearings which are susceptible to corrosion and require daily lubrication. The survey facilities reported a total direct RBC maintenance effort of approximately 2.9 hours per week, or 2.7 percent of total plant requirements, exclusive of corrective maintenance.

TABLE 6. RBC MANUFACTURERS SUGGESTED MAINTENANCE PROCEDURES (2)

SCHEDULE FOR MECHANICAL DRIVE UNITS

Daily

- Inspect all shafts, motors, gear reducers, bearings, etc., for operation; report any unusual noises or operation.

Weekly

- Inspect oil level in gear reducers and fill as needed.
- Wipe down oil and grease around unit.
- Grease bearings twice weekly.

Monthly

- Grease motor drive bearings.

Four Months

- Change oil in gear units; flush and fill as needed.
- Remove guards and inspect belts, belt tension, pulleys, and alighment; clean and adjust as needed.
- Remove guards and inspect drive chain and sprockets; clean, adjust tension, and align as needed.

Six Months

- Lubricate electric motors and speed reducer shaft.
- Take motor amperage reading and record.
- Inspect starters, disconnects, and switches; clean and tighten.
- Coat exposed metal parts with grease.
- Change oil in chain casing and speed reducer.

SCHEDULE FOR MECHANICAL DRIVE UNITS (continued)

Yearly

- Take insulation readings on motors and branch wiring.
- Remove all guards and touch up painting.
- Thoroughly clean and inspect units.

SCHEDULE FOR AIR DRIVE UNITS

Daily

- Inspect blowers, motors, couplings, etc., for operation; report any unusual noises or operation.

- Check rotating speed.

Weekly

- Inspect oil level on blowers and fill as needed.
- Wipe down oil and grease around unit.
- Check biofilm thickness and uniform aeration twice weekly.

Monthly

- Clean air intake filters.
- Grease motor drive bearings

Six Months

- Change oil in blowers.

- Lubricate electric motors.

- Take motor amperage readings and record.

- Inspect starters, disconnects, and switches; clean and tighten.

- Check coupling alignment.

- Coat exposed metal parts with grease.

Yearly

- Take insulation readings on motors and branch wiring.
- Remove all guards and touch up painting.
- Thoroughly clean and inspect units.
- Clean air headers and diffusers.

TABLE 7. RBC MAINTENANCE AND REPAIR RECORD

Plant ID No.	No. of shafts	Daily flow mgd	Labor requirements (person-hours)				
			Motors	Bearings	Reducers	Blowers	Total/week
1	10	1.9	1/Month	7/Week	2/6 Months	N/A	7+
4	2	0.2	1/Month	1/Month	1/Week	N/A	1.5
6	3	0.3	1/Month	1/Day	1/5 Months	N/A	3
7	12	1.3	1/Month	7/Week	1/Month	1/Month	7
9	4	1.0	1/6 Months	1/Week	1/6 Months	N/A	1
11	2	0.6	1/Month	2/Month	1/Month	N/A	1
12	4	1.8	1/Year	1/Week	1/Year	N/A	1
13	6	1.0	1/Year	7/Week	1/Year	N/A	7
14	8	2.0	1/Year	1/Week	1/Year	N/A	1
15	12	2.0	1/Year	2/Week	1/Week	N/A	3
16	2	0.4	1/Year	1/2/Week	N/A	1/2/Week	1
17	6	1.2	1/Year	1/Week	1/Year	N/A	1
18	6	2.7	1/Year	1/Week	1/Year	N/A	1
20	3	0.5	1/Year	1/Week	1/6 Months	N/A	1
21	8	0.9	1/Year	1/Week	N/A	1/Year	1
22	8	0.8	1/Year	1/Week	N/A	1/Year	1
23	4	0.3	1/Year	1/Week	N/A	1/Year	1
24	6	0.7	1/Year	1/Week	N/A	1/Year	1
25	6	0.5	1/Year	1/3 Months	N/A	1/Year	0.25
26	4	0.5	1/Year	1/3 Months	N/A	1/6 Months	0.25
27	5	0.6	1/6 Months	1/6 Months	1/6 Months	N/A	1
28	8	1.2	---	2/Week	0.5/Week	N/A	2.5

N/A - Not applicable

TABLE 8. RBC AND TOTAL PLANT OPERATIONS AND MAINTENANCE REQUIREMENTS (PERSON-HOURS PER WEEK; 40 HR/WK) (EXCLUDING CORRECTIVE MAINTENANCE)

Plant ID No.	No. of shafts	Design flow mgd	Total plant				RBC units				RBC hours as percent of total
			Superintendent	Operator	Other	Total	Superintendent	Operator	Other	Total	
1	10	1.9	47	47	15	109	3	3	2	8	7.3
4	2	0.2	12	25	5	42	0	1.5	0	1.5	3.6
6	3	0.3	45	45	---	90	0	2	1	3	3.3
7	12	1.3	13	37	150	200	1	1	5	7	3.5
9	4	1.0	20	84	40	144	---	1	2	3	2.1
11	2	0.6	30	90	---	120	---	---	1	1	0.3
12	4	1.8	20	40	120	180	---	---	5	5	2.8
13	6	1.0	20	120	---	140	---	---	1	1	0.7
14	8	2.0	40	40	60	140	---	---	1	1	0.7
15	12	2.0	20	---	161	181	---	---	3	3	1.6
16	2	0.35	40	20	20	80	---	---	1	1	1.3
17	6	1.2	40	---	160	200	---	---	1	1	0.5
18	6	2.7	40	---	80	120	---	---	1	1	0.8
20	3	0.5	40	---	20	60	---	---	1	1	1.7
21	8	0.9	40	40	---	80	---	---	1	1	1.3
22	8	0.8	45	45	---	90	---	---	2	2	2.2
24	6	0.7	40	100	---	140	---	---	5	5	3.6
25	6	0.5	40	---	---	40	---	---	1	1	2.5
26	4	0.5	40	---	---	40	---	---	1	1	2.5
27	5	0.6	40	40	40	120	---	---	1	1	0.8
28	8	1.2	3	10	30	43	---	---	2	2	4.7
29	3		---	40	---	40	---	---	1	1	2.5
					Totals	2,399				64	2.7

NOTE: Sample Size: 21 plants.
Correlation - Total person-hours per week to maintain RBC units vs design flow (mgd).
(r) for 0 to 0.9 mgd range = 0.65.
(r) for 1 to 3 mgd range = 0.05.

Corrective maintenance due to shaft or media failure was typically performed by plant personnel and not included in the facility survey maintenance requirements. Thus, those plants which experienced RBC equipment failures (detailed in Section 8) had higher maintenance requirements than were reported in the survey.

Maintenance requirements were increased at plant No. 7 due to the below-grade location and type of shaft bearing in use at this facility. The system was susceptible to flooding, which could submerge the bearings in wastewater. In order to gain access and perform maintenance on the bearings, the surrounding concrete had to be removed. In addition, the limited space provided in the RBC enclosure was not adequate for the work which had to be done (i.e., bearing replacement). Bearing maintenance is a continuing problem at this plant according to the operators.

No comparison could be made on RBC maintenance requirements between mechanical and air driven facilities due to the dissimilarity of plants surveyed (e.g., flow, number of shafts, facility operating hours, etc.). However, it appears that air-driven units require less maintenance time due to the reduction of mechanical equipment (i.e., drive motors, reducers, V-belts, or drive chains involved for each unit), but increased time in maintaining RBC rotational speed.

Corrective vs. Preventive Maintenance --

Preventive maintenance is that conducted routinely on a scheduled basis to prevent equipment failures. Corrective maintenance is work required after the equipment fails. This condition generally requires more extensive work, work that may be required at odd hours of the day or night, and it could shut down a critical piece of equipment.

As detailed in Section 8 (Table 12), corrective maintenance was practiced at 70 percent of the facilities surveyed. Plant No. 15 experienced severe problems in which all 12 shafts and media were replaced due to failures. The manufacturer is no longer marketing RBC units and the system has been redesigned by another manufacturer.

Corrective maintenance was caused by the design of the equipment in all the surveyed plants. Corrective maintenance directly increases the O&M cost of the facility, due to increased manpower requirements and replacement costs due to premature replacement and the need for contracted services.

Process Control

The RBC process is an inherently simple but effective means for wastewater treatment that does not require the operator to perform process testing with subsequent control or adjustment of wastage and return rate, air, and pumping rates. RBC equipment is normally preceded by some type of primary treatment and normally followed by a final clarifier. Unless the other processes and related equipment are operated and properly maintained, the RBC process and equipment cannot be expected to perform as designed. The RBC process is normally operated on a once-through basis with no recycle of effluent. Also, since the attached biofilm is continuously growing on the media, there is no requirement for sludge recycle to maintain the biological population. The absence of recycle requirements serves to provide for uncomplicated process operation.

In a normal operating mode, an RBC unit is designed to meet effluent criteria without continuous operator attention for process control. Those facilities surveyed that were meeting design removal conditions or effluent discharge criteria practiced minimal operational control of the RBC process.

Of the plants surveyed, the respondents did not typically consider the operation of the remaining unit processes when responding to process control techniques or maintenance requirements for RBC's. They considered these activities to be separate plant function. Included among these activities, for example, are the proper operation of aerobic/anaerobic digesters, clarifiers and sludge removal systems, and influent pumping.

Improvement to RBC performance was achieved in many plants through the use of chemicals, supplemental aeration techniques, or adjustments to other unit operations. However, there were no provisions for periodic adjustments to the mechanically-driven RBC units themselves. In the case of air-drive units, air flow rates required adjustments to maintain proper speed.

Process control procedures for proper RBC performance require consideration of the following:

1. Soluble organic loading on first-stage media.
2. Average hydraulic loading versus peak hydraulic loading.
3. Rotational velocity.
4. Dissolved oxygen concentration in the first stage.

Process Control Examples --

Survey experience indicates that RBC process problems are primarily organic-overloading related including improper design, digester supernatant return, septage treatment, and in-plant solids accumulations due to inadequate solids removal/disposal facilities. Discussions of process problems experienced at several facilities follow.

Plant No. 7 has experienced numerous problems. The RBC system was designed for carbonaceous and ammonia-nitrogen oxidation. Odor due to sulfide generation was a problem at the plant, initially, due to long collection system detention times resulting in a septic influent. Potassium permanganate addition was subsequently implemented at the outlying pump stations to control septic conditions. In addition, no primary clarification (only coarse screening) was provided. Suspended solids settled out in the influent/effluent channels of the RBC units and in the RBC tanks themselves. When settled solids accumulate, anaerobic decomposition results in the release of hydrogen sulfide. Dissolved oxygen concentration in the influent channels was less than 1.0 mg/L. The lack of adequate D.O. and the presence of sulfides contributed to the growth of Beggiatoa (and Thiotrix). This growth effectively displaced the carbonaceous bacteria necessary for BOD reduction to the latter stages. Two-thirds of the discs were covered with the "nuisance" growth. In addition, the tip clearance of the media in the tanks was 14 inches rather than the 4 inches of later designs, resulting in lower levels of mixing and consequent solids deposition. The solids accumulation was so severe that the tips of the first stage disc were wiped clean of biomass. The final disc of each pass had a normal brown growth. However, nitrification was inhibited, as evidenced by effluent ammonia-nitrogen concentrations in the 6- to 14-mg/L range.

Plant personnel have responded to these difficulties with limited success. Hydrogen peroxide was added at several locations in the plant and, to further increase D.O. levels, coarse bubble aeration was installed in the distribution channels prior to and between the RBC units. Dissolved oxygen concentrations have increased from 1.1 mg/L in the first stage to 2.5 mg/L in the third stage, and effluent BOD values have improved to below 30 mg/L in the discharge. However, substantial Beggiatoa growth still predominates on the first two stages and ammonia conversion to nitrates has not been activated.

Plant No. 10 also experienced D.O.-limiting conditions resulting in Beggiatoa growths and reduced RBC performance. Dissolved oxygen concentrations in all stages were less than 0.5 mg/L, partially as a result of plant operating practice of returning unsettled aerobic digester liquor to the RBC units. Supplemental aeration was installed under the first two shafts and digester operation was modified to reduce in-plant solids recycle. The biomass on the discs has improved and Beggiatoa growths have been eliminated, according to observations by the state agency. Effluent quality has been reported to have improved significantly, in terms of clarity and settleability; effluent soluble BOD_5 levels have also decreased by 50 percent.

Plant No. 9 experienced influent surging of septic wastewater and sidestream problems from an aerobic digester which contributed to organic overloads and nuisance organism growth on the RBC units. Although the plant was meeting effluent BOD and suspended solids limitations, it was not meeting ammonia-nitrogen limits (actual 15 mg/L versus 2.0 mg/L stipulated in NPDES permit) due to displacement of carbonaceous-removing bacteria. The facility used four shafts in series, and the nuisance growths dominated the first two discs. A biological examination of the first two revealed a heavy greyish/black biofilm consisting of stringy grey filaments and dispersed septic bacteria (Beggiatoa/Thiotrix). The last two discs had a sparse brown biofilm which revealed a balanced zoogleal population.

The influent wet-well and flow channels to the RBC units were designed for an ultimate flow of 5.2 mgd; however, current flows averaged 0.8 mgd. Excessive detention times exist in the wet well and influent flow channel to the RBC units, resulting in the units being "slugged" by intermittent septic wastewater loads.

The plant was staffed for 8 hours per day coverage, and the operator usually recirculated effluent from the bottom of the chlorine contact tank between 4:00 P.M. and 8:00 A.M., in order to shorten the detention time in the influent wet well during typically low flow rate conditions. This practice aided in reducing septicity of the influent; however, it resulted in diurnal variations in organic load due to the dilution effect of the contact water. The treatment process was not operating under stable conditions.

Additionally, aerobic digester liquid level is controlled by an overflow pipe which returns digester supernatant back to the influent wet well. The recycled digester supernatant contained a substantial organic load, which also contributed to the problem.

Process Control Tests--

An RBC system for secondary wastewater treatment does not require routine laboratory analysis as a means of operational control. Sludge recirculation is not required to assure BOD reduction and/or nitrification. Similarly, effluent recycle is not required. The biofilm on the media adjusts to the changing loading characteristics in the wastewater, thus releasing the operator from performing mandatory control tests. Extensive records, though not necessary for daily operation, become important when process problems develop.

The discharge of sidestream effluents to the RBC unit, particularly from solids handling and treatment processes, can change the RBC loading and final effluent quality. For example, anaerobic digester supernatant may add a significant amount of ammonia and soluble BOD, and filtrate from sludge dewatering devices may also add significant amounts of soluble BOD. The type and nature of each sidestream must be quantified and the resulting organic and hydraulic loading evaluated for the entire RBC system. Sidestream flows adversely affected the performance of eight of the RBC facilities surveyed. Additional discussion concerning sidestream quantification is presented in Section 10.

Microbial examination of biomass -- The typical biomass observed at properly operating facilities during the survey was a golden-brown shaggy mass, which is associated with carbonaceous BOD removal. Film thickness in each stage varied in proportion to the organic loading applied. In the plants that incorporated nitrification in the plant process, the growths on the later stages were much thinner, shaggy, irregular in thickness, and had a reddish-brown appearance.

The development of a white/grey biomass was shown to be an indication of impending process problems. There is no immediate concern if the growth appears on small areas of the media. If the white/grey biomass appears on a substantial portion (e.g., 40 percent or more) of the media, reduced process performance will result. This is an indication of septic wastewater, high sulfide concentrations (which may be a result of septic wastewater or an industrial discharge), or organic overloading of the first stage, which produces dissolved oxygen limitations leading to the predominance of nuisance growths.

Microscopic examination of the biofilm will aid in fully understanding the conditions noted during visual observations. A healthy biomass will have good bacterial floc, numerous free swimming ciliates, stalk ciliates, and, in the latter stages, rotifers and nematodes. Nuisance organisms appear as stringy grey/black hair-like bacteria or fungi filaments. These organisms are easy to recognize under a microscope.

Dissolved oxygen concentration -- Certain parameters not normally found to be monitored on a periodic basis can be crucial to the performance of an RBC plant. One such parameter, influent dissolved oxygen, was recorded at only one of the plants studied.

It is recommended that the dissolved oxygen concentration of the wastewater beneath the rotating media be periodically measured to ensure sufficient oxygen transfer is occurring for effective treatment. This measurement should be taken daily. Dissolved oxygen concentrations greater than 1.5 to 2.0 in the first stage and increasing through subsequent stages are indicative of nonoverloaded systems with sufficient oxygen supply. Additional discussions concerning D.O. are presented in Sections 4 and 10.

Sulfates -- The reduction of sulfates to hydrogen sulfide under anaerobic conditions has been known to cause odor and corrosion problems in sewers and treatment plants. Hydrogen sulfide, along with free sulfur, poses an additional problem to RBC facilities. Since *Beggiatoa* have the capacity to use both as energy sources, its presence will become predominant resulting in a reduction in the amount of SBOD removal.

The presence of sulfide in the wastewater feed to biological treatment processes can cause a problem which results in reduced organic removal efficiencies. The RBC process appears to be quite sensitive to the presence of sulfides. The operator should be aware of the presence of sulfides in the influent wastewaters and should be prepared to control possible harmful effects. The most common methods used to control sulfides are based on the oxidation of the sulfides to free sulfur by hydrogen peroxide, chlorination, supplemental aeration, or pre-aeration. Supplemental aeration is most advantageous when the wastewaters contain high concentrations of soluble organic substrate which depresses the dissolved oxygen level in the first stage. This practice will minimize the need to use sulfate as a source of oxygen.

pH -- During the site visits, interstage pH measurements were taken and all values were in the range of 6.7 to 8.5. The highest influent pH measured was 8.2 at plant No. 7 where sodium hydroxide was added to the plant influent (prior to equalization) due to wide fluctuations in influent pH and to raise the pH prior to the RBC units to promote nitrification. The lowest influent pH to the RBC units was measured at 6.7 in plant No. 13.

Severe variations in influent pH can cause a loss of active biomass on the media. Municipal wastewaters typically have a pH which is relatively constant; however, it ranges from 6.5 to 8.5, depending on the source of the municipal water. Excessive variations in pH from these values have been attributed to industrial discharges to the collection system

It has been reported that pH values below 6.5 have been shown to inhibit nitrification. pH monitoring is essential where the raw municipal wastewater is below 6.5 to ensure that a proper environment for the nitrification organisms is maintained.

Soluble and total BOD -- Both SBOD and BOD are important for assessing the influent organic loading, the impacts of which are discussed in depth in Section 10. Interstage SBOD data are necessary to define performance problems. This is particularly true in nitrification systems since the presence of high quantities of SBOD in the later stages will result in microbial populations which do not contain sufficient nitrifying microorganisms to oxidize the ammonia-nitrogen.

Temperature -- Wastewater temperatures below 55°F will result in a reduction of biological activity and a decrease in organic removal. When the temperature drops, biological growth becomes slower, requiring a greater amount of biomass (or media area) to remove the same amount of BOD. This is one of the reasons RBC units are covered with individual housings or located in buildings to protect the biological growth from low temperatures and to avoid excessive heat loss from the wastewater.

SECTION 7

EXISTING DESIGN PROCEDURES

Existing RBC design procedures can be divided into three general categories: empirical approaches, statistical approaches, and theoretical approaches. Since most municipal facilities have been designed by empirical methods, an examination of performance history relative to empirical design was possible. Statistical approaches have been proposed as a design methodology, but no full-scale field application of this method has been identified. Theoretical approaches have been proposed and utilized in pilot plant operations, but little data exists on their application to full-scale operating facilities. Statistical and theoretical approaches were reviewed in previous sections in light of their process simulation merits.

EMPIRICAL DESIGN APPROACHES

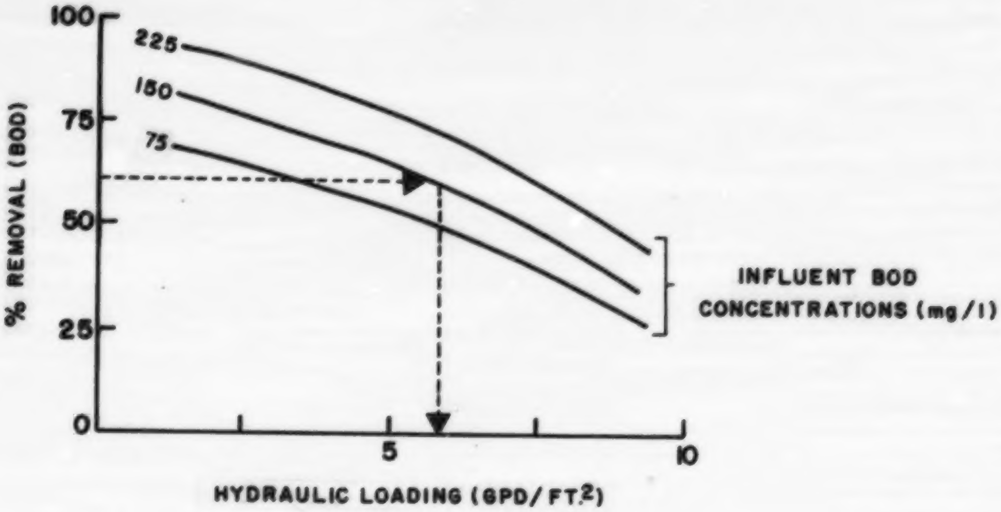
Empirical design approaches were developed by manufacturers for engineers to use in applying their equipment to municipal RBC wastewater treatment facilities. The engineering community utilized these approaches as methodologies without fully understanding many of the performance parameters. Thus, many of the existing facilities have been sized based on manufacturers empirical design approaches.

Design Curves

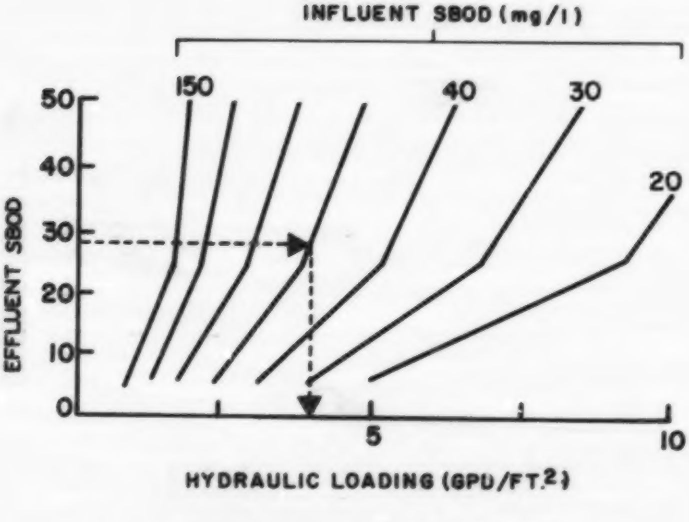
Most empirical methods are based on design curves developed by RBC equipment manufacturers. Manufacturer design curves define effluent concentrations (soluble or total BOD) in terms of applied hydraulic loading and influent concentration. Examples of these curves are illustrated in Figure 9. Starting with a desired efficiency or effluent concentration and a given influent concentration, the designer simply selects the defined hydraulic loading which establishes surface area requirements.

These curves are based on field tests and have been established by developing relationships between organic removal rates, hydraulic loading, and influent concentration.

All major domestic suppliers of RBC equipment were contacted to provide the data base used to develop their current design curves.



BASIS: TOTAL BOD



BASIS: SOLUBLE BOD

Figure 9. Effluent design curves.

The Autotrol Corporation was the only manufacturer to cooperate with this request. They provided the field data and empirical methodology that represent the basis of their present design recommendations (2). By monitoring influent and effluent soluble BOD data, as well as hydraulic loading, at five full-scale operating RBC plants, Autotrol defined two regimes and developed a linear relationship between organic loading and effluent soluble BOD. To facilitate using the curve as a design method, organic loading was separated into component variables, influent SBOD and hydraulic loading. These and other manufacturers' curves (40) are compared to observed field performance and evaluated in Section 8. The effluent SBOD concentrations predicted for given organic loadings using different manufacturers' curves were compared. The results of that comparison are presented in Figure 10.

Temperature Correction

Surface area corrections are recommended for wastewater temperatures below 55°F. Figure 11 illustrates three current temperature correction curves, as well as one manufacturer's previous correction recommendation. The upper curves simulate greater reductions in reaction rates at lower temperatures. Correction factors shown for various temperatures are used to increase the recommended surface area derived from curves in Figure 9.

In addition to temperature corrections for cooler wastewaters most manufacturers require that wastewater temperatures not exceed 90°F. These higher temperatures can damage RBC media (polyethylene); however, they are normally not a problem in municipal wastewaters.

Staging

One to four stages is recommended in most design manuals. A larger number of stages is recommended to achieve higher removal rates. Guidelines for staging recommended by manufacturers are listed in Table 9. Definitive relationships between staging and design curves have not been established and reasons for the recommendations listed in Table 9 have not been documented.

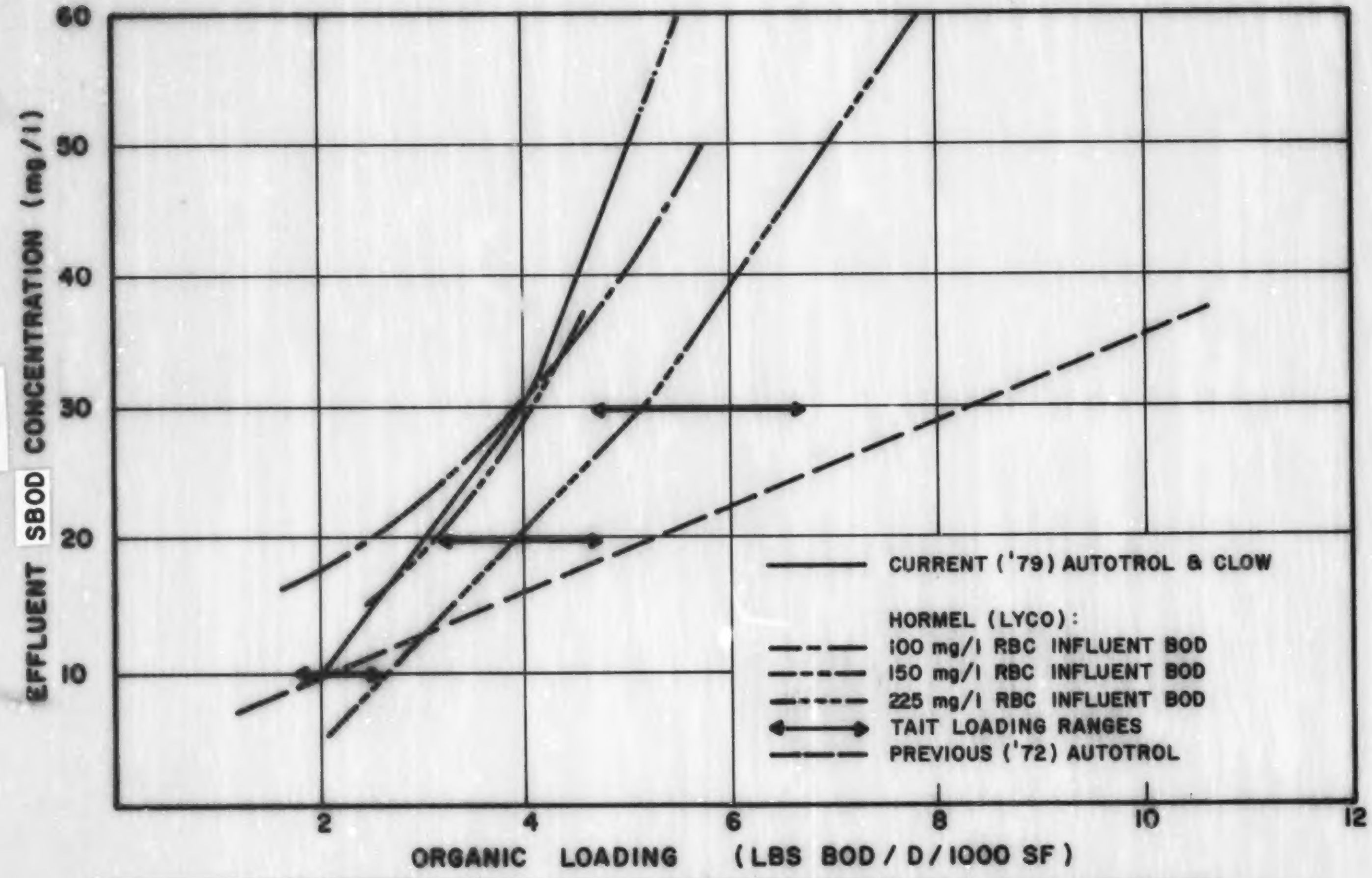


Figure 10. Comparison of manufacturers' RBC design curves - effluent BOD concentration vs. organic loading.

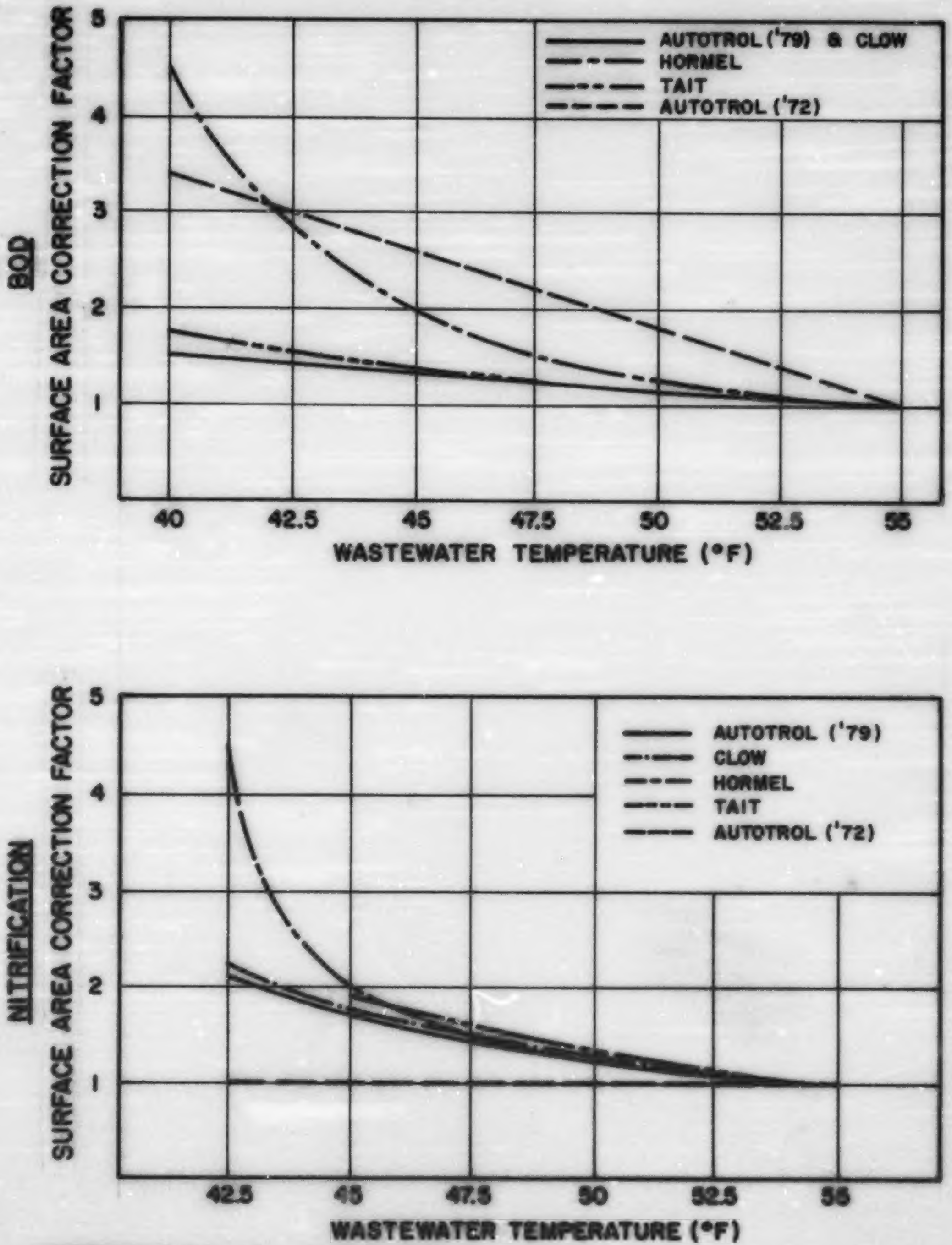


Figure 11. Manufacturers' BOD and nitrification temperature correction curves.

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TABLE 9. MANUFACTURER STAGING RECOMMENDATIONS

Reference 2

Design effluent soluble BOC mg/L	Recommended minimum number of stages
< 10	3 or 4
10-15	2 or 3
15-25	1 or 2
> 25	1

Reference 49

Percent reduction	Recommended number of stages
Up to 40%	1
35 to 65%	2
60 to 85%	3
80 to 95%	4
Over 95%	(Consult)

Organic Loading Limitations

Recognizing the potential for overloading stages, maximum organic loadings are recommended by one manufacturer, Autotrol (2), which limits the total loading to the RBC system. Examples of soluble BOD limitations presented are as follows:

Media type	Mechanical system	Air drive system
Standard density[1]	4.0 lb/day/1,000 sf	5.0 lb/day/1,000 sf
High density[2]	1.7 lb/day/1,000 sf	2.5 lb/day/1,000 sf

[1] First stage loading limits.
[2] Overall plant loading limits.

SECTION 8

REVIEW OF CURRENT PROCESS AND EQUIPMENT PERFORMANCE

This section contains a review of both process and equipment performance data collected from RBC facilities during the course of this investigation. The surveyed plants can be divided into two overlapping groups. The first group supplied process performance data and the second group supplied equipment performance data.

PROCESS REVIEW

RBC facilities have been operating in this country for approximately 10 years. To assess their performance, a review of facilties that were exceeding 80 percent of their design flow was undertaken. The intent was to assess the performance of RBC's under design loading conditions.

Data Sources

Many facilities reaching design flows are older facilities with flows generally less than 0.1 mgd. In addition, many of these facilities infrequently monitor performance and, in some instances, monitor final effluent only. A total of 16 facilities operating at 80 percent of their design flow and which monitored influent and effluent on a regular basis were identified. Table 10 presents these facilities including their design and actual loadings, sampling locations, and monitoring frequencies. The majority of the collected data came from monitoring reports submitted by the plant personnel to the respective state agency. Data from plant No. 5 came from an in-plant survey by a local consultant (52). Influent sampling locations varied from facility to facility. Five of the 16 facilities monitored primary clarifier influent and effluent; four monitored influent to screens (these plants did not have primary clarification); and seven monitored primary clarifier influent. Effluent sampling locations were prior to chlorination in all but three facilities.

TABLE 10. PROCESS SURVEY: RBC FACILITIES

Plant ID No.	Design flow mgd	Average influent BOD concentration[5] mg/L	Actual percent of design flow to RBC	Design hydraulic loading gpd/sf	Design final clarifier overflow rate gpd/sf	No. of stages	Rotational velocity rpm	Effluent sampling location	Monitoring frequency
1	1.90	145	108	1.72	484	4	1.60	After Final Clarification and Chlorination	Daily
2	1.30	128	85	2.17	392	2	1.70	After Final Clarification	Weekly
3	0.65	122	28	3.70	880	4	1.50	After Final Clarification	Weekly
4	0.20	95	35	1.18	476	4	1.60	After Final Clarification and Sand Filtration	Weekly
5	0.50	NA	95	2.02	510	4	1.80	After Final Clarification	Monthly
6	0.22	152	83	1.05	140	4	1.50	After Final Clarification	Daily
7	1.30	228	92	1.13	670	3	1.20	After Final Clarification	Weekly
8	0.38	70	136	2.85	405	4	1.50	After Final Clarification and Chlorination	Daily
9	1.00	144	79	2.50	354	4	1.60	After Final Clarification	Monthly
10	0.50	233	112	1.56	520	3	1.68	After Final Clarification	Monthly
11	0.65	140	87	1.00	424	1	1.50	After Final Clarification	Weekly
12[1]	1.75	180	78	5.72	784	4	1.60	After Final Clarification and Chlorination	Weekly
13	1.00	NA	66	1.89	558	6	1.80	After Final Clarification and Chlorination	Daily
14	2.00	97	66[2]	2.50	510	3	1.70	After Final Clarification	Daily
15	2.80	194	63[3]	2.33	432	4	1.60	After Final Clarification	Daily
16[4]	0.35	114	98	1.75	460	4	1.20	After Final Clarification	Daily

[1] Treats trickling filter effluent.
[2] Only 1/2 plant capacity being used.
[3] Only 2/3 plant capacity being used.
[4] Air drive system.
[5] Plant raw influent concentration.

RBC Reliability and Process Performance

Reliability --

Data from these 16 plants were analyzed to determine the reliability of RBC facilities approaching or at design flow. The reliability of the RBC plant is represented by the probabilistic distribution of percent BOD removal and effluent BOD concentration and their relationship to NPDES criteria (85 percent BOD removal and 30 mg/L BOD effluent concentration).

Municipal wastewater treatment plant performance data (BOD, SS) are typically plotted on log probability paper since this type of data have been shown to be log normally distributed (78). Monthly average percent BOD removals in terms of overall plant removal efficiencies (raw influent to final influent) and final effluent concentrations for each facility, presented in Appendix B, were utilized to prepare arithmetic and log probability plots to define the appropriate data distribution (i.e., normal or log normal). The data were better represented by the log probability plot. The results of the log plot are presented in Table 11 along with a brief description of performance limitations in each plant.

Results show that plants have greater success in complying with effluent concentration criteria (maximum 30 mg/L monthly average) than they have with percent BOD removal standards (85 percent minimum). This is primarily due to diluted influent organic concentration resulting from infiltration/inflow problems. Other reliability problems result from organic overloads and/or sidestream problems. A cumulative probability distribution for 15 of the survey plants (plant No. 12 was excluded from this analysis because the RBC units are a polishing process which follows an existing trickling filter operation) is presented in Figure 12. The mean value of percent BOD removal was 82 percent, with values ranging from 75 percent to 90 percent for one standard deviation. The mean effluent concentration was 18 mg/L, with one standard deviation varying between 12 and 28 mg/L. The cumulative plot also indicates that the plants exceeded effluent criteria 12 percent of the time and failed to meet percent BOD removal 67 percent of the time.

TABLE 11. PLANT PERFORMANCE AND LIMITING CONDITIONS

Plant ID No.	Monthly average percent BOD removal[3]	Range of standard deviation[2]	Percent of time not meeting 85% removal criteria	Monthly average effluent concentration mg/L	Range of standard deviation[2]	Percent of time effluent exceeds 30 mg/L	Performance limitation
1	88	87-90	1	15	13-17	0	Consistently good performance with average removal efficiencies dropping off with decreasing influent BOD strength.
2	86	70-100	44	9	4-23	10	Occasional upsets in removal rates not due to RBC performance, traced to oil leaked to collection system.
3	74	64-86	84	26	17-39	38	Intermittent sludge lagoon recycle and high soluble to total BOD fractions in influent waste lead to organic overloads.
4	85	77-93	49	10	6-17	1	Infiltration/inflow problems hydraulically overload plant and dilute influent waste strength, causing poor removal rates but adequate effluent quality.
5	88	85-91	22	29	24-35	62	RBCs are organically overloaded producing nuisance organism growths in the first stage.
6	91	88-94	1	11	7-16	1	Removal rates and effluent concentration consistently meet NPDES criteria through a range of influent BOD from 0 to 350 mg/L.
7	88	82-93	20	24	18-32	20	High influent BOD strength and solids accumulations in RBC tanks lead to organic overloads and nuisance organism growths.
8	68	56-81	90	20	15-27	7	Infiltration/inflow problems hydraulically overload plant and dilute influent waste strength, causing poor removal rates, but adequate effluent quality.
9	80	73-88	75	25	15-39	33	Septic wastewater and sidestream problems from an aerobic digestor lead to organic overloads and nuisance organism growths on the first stage.
10	88	85-91	10	27	21-35	35	Occasional upsets are due to unsettled aerobic digestor supernatant returned to the head of the plant.
11	77	70-85	84	28	20-45	48	Water taps left running to prevent freezing cause hydraulic overloads and low waste strength, coupled with digestor problems; result in poor performance.
12[1]	83	77-89	68	27	22-32	25	RBCs treat trickling filter effluent, producing acceptable final effluent; 66 percent removal is only slightly less than design due to decreased treatability of trickling filter effluent.
13	89	81-98	28	8	6-13	1	Infiltration/inflow problems hydraulically overload plant and dilute influent waste strength, causing poor removal rates, but adequate effluent quality.
14	72	62-85	85	23	16-32	20	Infiltration/inflow problems hydraulically overload plant and dilute influent waste strength, causing poor removal rates.
15	87	81-94	36	17	11-25	7	Occasional organic overloads cause D.O.-limiting conditions and nuisance organism growths, but average performance is acceptable.
16	76	69-83	90	23	15-35	26	Substantial infiltration/inflow problems hydraulically overload plant and dilute influent waste strength, causing poor removal rates.

[1] Not included in cumulative data analysis.

[2] Because the distribution is a log function, the value of the standard deviation added to the mean is greater than the standard deviation below the mean. For this reason, the standard deviation, or 68.4 percent confidence limits, are reported as a range of values.

[3] Represents overall percent removal (raw BOD to final effluent BOD).

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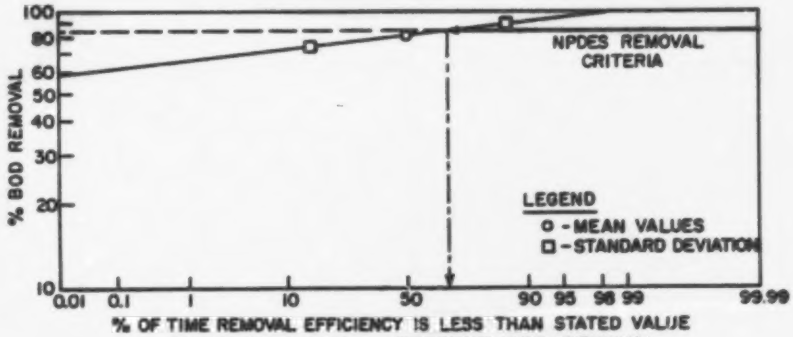
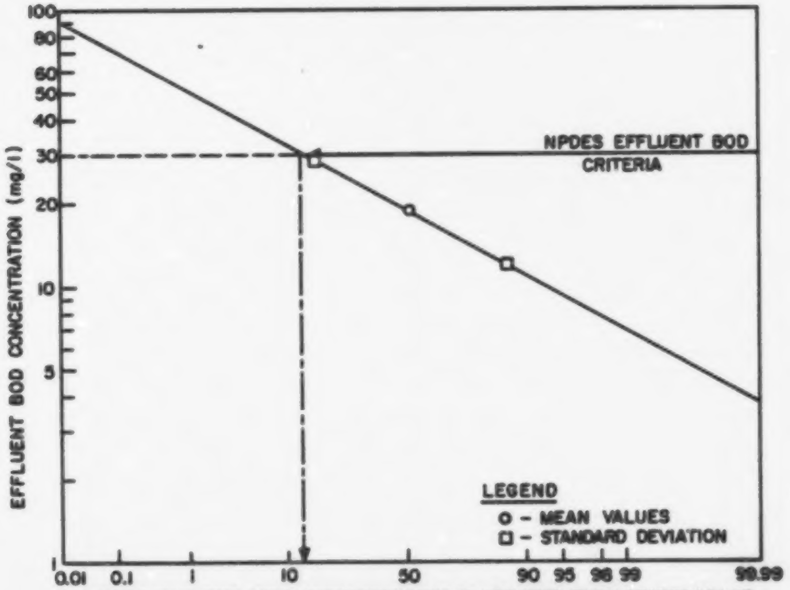


RELIABILITY PLOT - PERCENT BOD REMOVAL
(BASED ON A 30-DAY AVERAGE)



RELIABILITY PLOT - EFFLUENT CONCENTRATION
(BASED ON A 30-DAY AVERAGE)

Figure 12. Reliability plots for percent BOD removal and effluent BOD for 15 plants surveyed.

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TYPING GUIDE SHEET

Process Performance --

RBC process performance can be expressed in terms of design parameters which assist in defining surface area requirements. An analysis of RBC performance was undertaken to define the design parameters which correlate best with actual RBC performance. Parameters most often associated with RBC performance are hydraulic loading and organic loading.

To evaluate RBC process performance it is necessary to evaluate the loadings to the RBC process and the quality of effluent produced. Since some of the plant data did not provide quality data with regard to primary clarifier effluent it was necessary to adjust these data. Of the 16 plants surveyed, five provided sufficient data to adequately describe actual influent conditions to the RBC units (plants No. 1 and No. 7 provide no effective primary BOD removal; plants No. 13, No. 14, and No. 16 monitor primary clarifier effluent), and effluent quality from the final clarifier. To use the data from the remaining facilities, it was necessary to assume that a 25 percent reduction in BOD occurred in the primary clarifier to obtain the influent quality to the RBC unit.

Hydraulic loading -- Hydraulic loading (gpd/sf)[1] is a parameter which is inversely related to the liquid detention time in the RBC reactor. To assess the overall effect of hydraulic loading on performance, the graphical relationship between BOD removal efficiency and hydraulic loading, and mass BOD removal and hydraulic loading were analyzed.

Hydraulic loading and percent BOD removal -- Monthly averages of BOD removal efficiencies and hydraulic loading were computed for each of the 16 plants. The data were segregated into four RBC influent BOD ranges[2]: 0 to 74 mg/L; 75 to 124 mg/L; 125 to 174 mg/L, and 175 to 350 mg/L. This was done to account for the potential effect of varying reactor concentrations on substrate diffusion and overall performance. A linear regression analysis of BOD removal efficiencies versus hydraulic loading was performed on the data from all 16 plants. The results are tabulated in Appendix C and are depicted graphically in Figure 13. The length of the abscissa was limited to 95 percent of the hydraulic loading values reported for each influent BOD range. The regression line is depicted for each concentration range along with a tabulation of the correlation coefficients and the 95 percent confidence limits.

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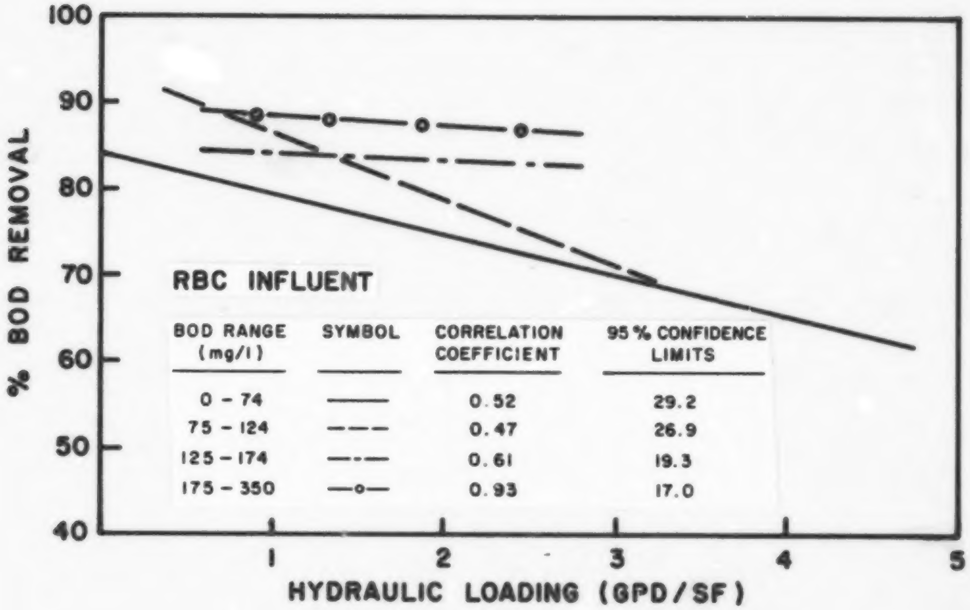
[1] Represents gallons per day per square foot of surface area.

[2] RBC influent BOD refers to primary clarifier effluent or 0.75 x (raw BOD) to account for 25 percent primary clarifier removal.



RBC INFLUENT

BOD RANGE (mg/l)	SYMBOL	CORRELATION COEFFICIENT	95 % CONFIDENCE LIMITS
0 - 74	———	0.52	29.2
75 - 124	— — —	0.47	26.9
125 - 174	—·—	0.61	19.3
175 - 350	—o—	0.93	17.0

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Figure 13. Results of linear regression analysis - percent BOD removal vs. hydraulic loading.

Hydraulic loading and mass BOD removal -- Using data from the same 16 plants, monthly averages of mass BOD removal rates (lbs BOD removed/day/1,000 sf) versus hydraulic loading were computed for the same four RBC influent BOD ranges: 0 to 74 mg/L; 75 to 124 mg/L; 125 to 174 mg/L, and 175 to 350 mg/L. A linear regression analysis of the cumulative data was undertaken; the results are tabulated in Appendix C and are depicted graphically in Figure 14. The length of the regression line in Figure 14 was limited to 95 percent of the hydraulic loading values reported for each influent BOD range. The 95 percent confidence limits and the correlation coefficient are also tabulated on the figure. This method of displaying performance (Mass BOD Removal vs. Hydraulic Loading) is a common tool for both designers and researchers. High correlation coefficients, ranging between 0.85 and 0.98, have previously been reported using these parameters (55).

Organic loading -- Organic loading has recently been promoted as an effective empirical design format (55, 56). Organic loading was evaluated by using the data from the same 16 facilities. Monthly averages of mass BOD applied versus mass BOD removed, expressed as lbs per day per 1,000 square feet, were analyzed.

A regression analysis of the two parameters was performed for data from the 16 plants. Results are listed in Appendix C as Mass BOD Removed vs. Mass BOD Applied. The regression line, including the 95 percent confidence limit and the correlation coefficient, is displayed in Figure 15. The regression line presented in Figure 15 was developed using influent and effluent BOD from multiple stage plants and does not reflect staging effects.

Process summary -- The regression analysis, presented in Figure 13, of percent BOD removal versus hydraulic loading, resulted in poor correlation in all three lower influent BOD concentration ranges, represented by the respective correlation coefficients, and good correlation (0.93) in the 175 to 350 mg/L influent BOD range. At the 95 percent confidence limit, the data also showed the least variability (± 17 percent BOD removed) in the 175 to 350 mg/L range.

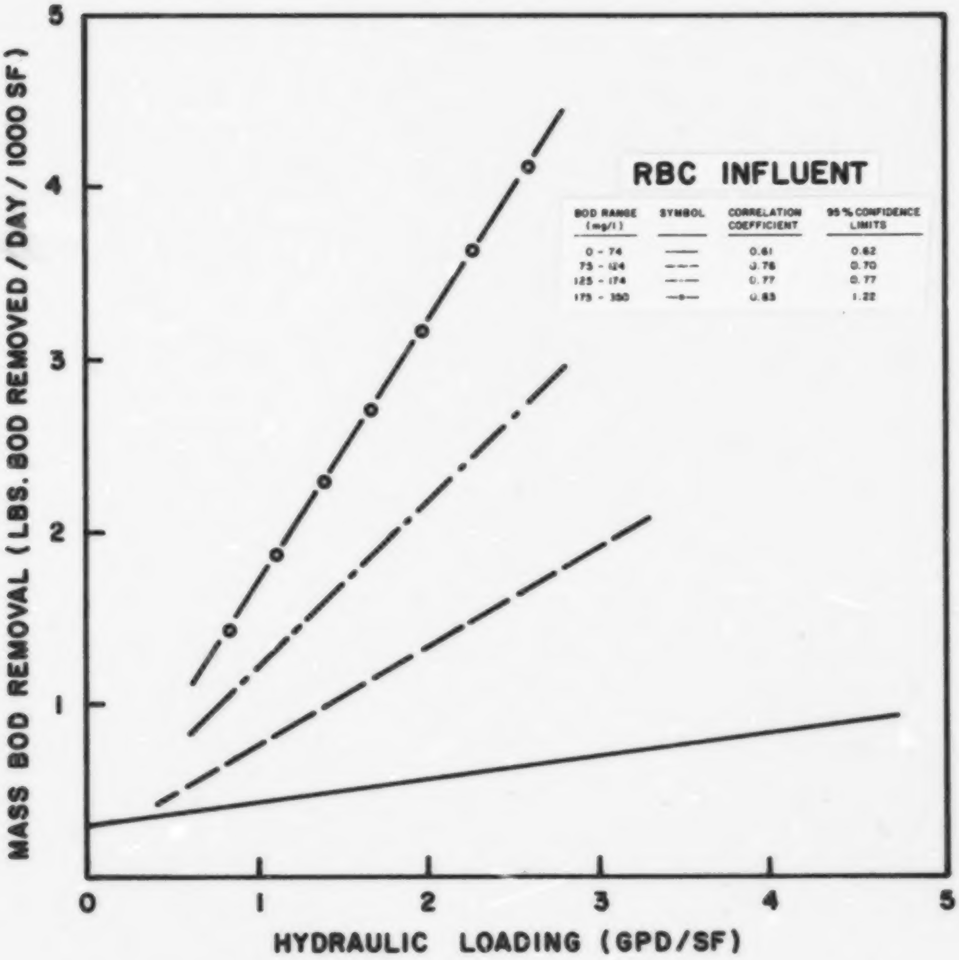

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Figure 14. Results of linear regression analysis - mass BOD removal vs. hydraulic loading.

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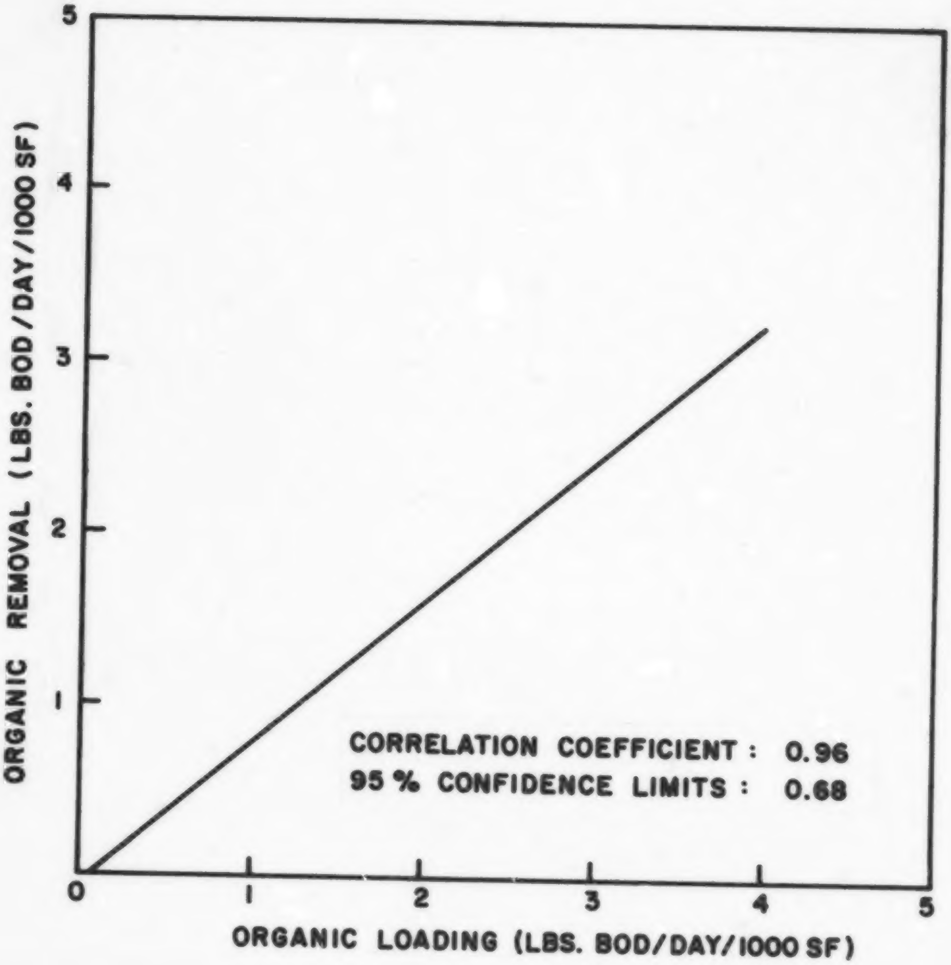

Figure 15. Results of linear regression analysis - organic removal vs. organic loading.

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14

The analysis of organic removal versus hydraulic loading presented in Figure 14 resulted in reasonable correlation (approximately 0.8) in the three highest concentration ranges and the poorest correlation (0.61) in the 0 to 74 mg/L range. Data confidence, represented by the 95 percent confidence limits, also showed the least variability in the higher concentration ranges.[1]

The analysis of organic removal versus organic loading in Figure 15 resulted in a high (0.96) correlation coefficient.

A comparison of the three methods of analysis indicate that organic removal versus organic loading gave the best linear correlation. The linear regression analysis of organic removal versus hydraulic loading correlated better than percent BOD removal versus hydraulic loading when influent BOD concentrations were subdivided into the four ranges examined.

A graphical example of the sensitivity of performance prediction to loading parameters is presented in Figure 16. Figure 16 illustrates the influence of the mass BOD removal rate defined as lbs BOD removed per day per 1,000 sf on mg/L BOD removal at various hydraulic loadings. The figure constructed is represented by equation 4:

$$\frac{\Delta C}{O.R.} = \frac{1}{(H.L. \times 0.00834)} \qquad (4)$$

where

O.R. = BOD removal rate (lbs/day/1,000 sf)
H.L. = hydraulic loading (gpd/sf)
ΔC = BOD concentration reduction (mg/L)
0.00834 = conversion factor for units (lbs/1,000 gal.)

The term ΔC/O.R. represents the mg/L of BOD reduction per lb BOD removed per day per 1,000 sf. This term defines the sensitivity of mg/L BOD removed to mass BOD removal rate and is constant for a given hydraulic loading as shown in Equation 4 and Figure 16.

For example, at a hydraulic loading of 1 gpd/sf, ΔC/O.R = 120, which indicates that 120 mg/L of BOD is removed for every lb BOD per day removed per 1,000 sf. A difference of 0.2 lbs BOD per day per 1,000 sf between design and actual would result in a 24 mg/L difference between predicted and actual BOD concentration. As a result, small errors in mass removal rates result in large errors in effluent concentration, especially at the low hydraulic loadings where most facilities operate.

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[1] Evaluated as the confidence limit divided by the average organic removal (average Y-value presented in Appendix C).

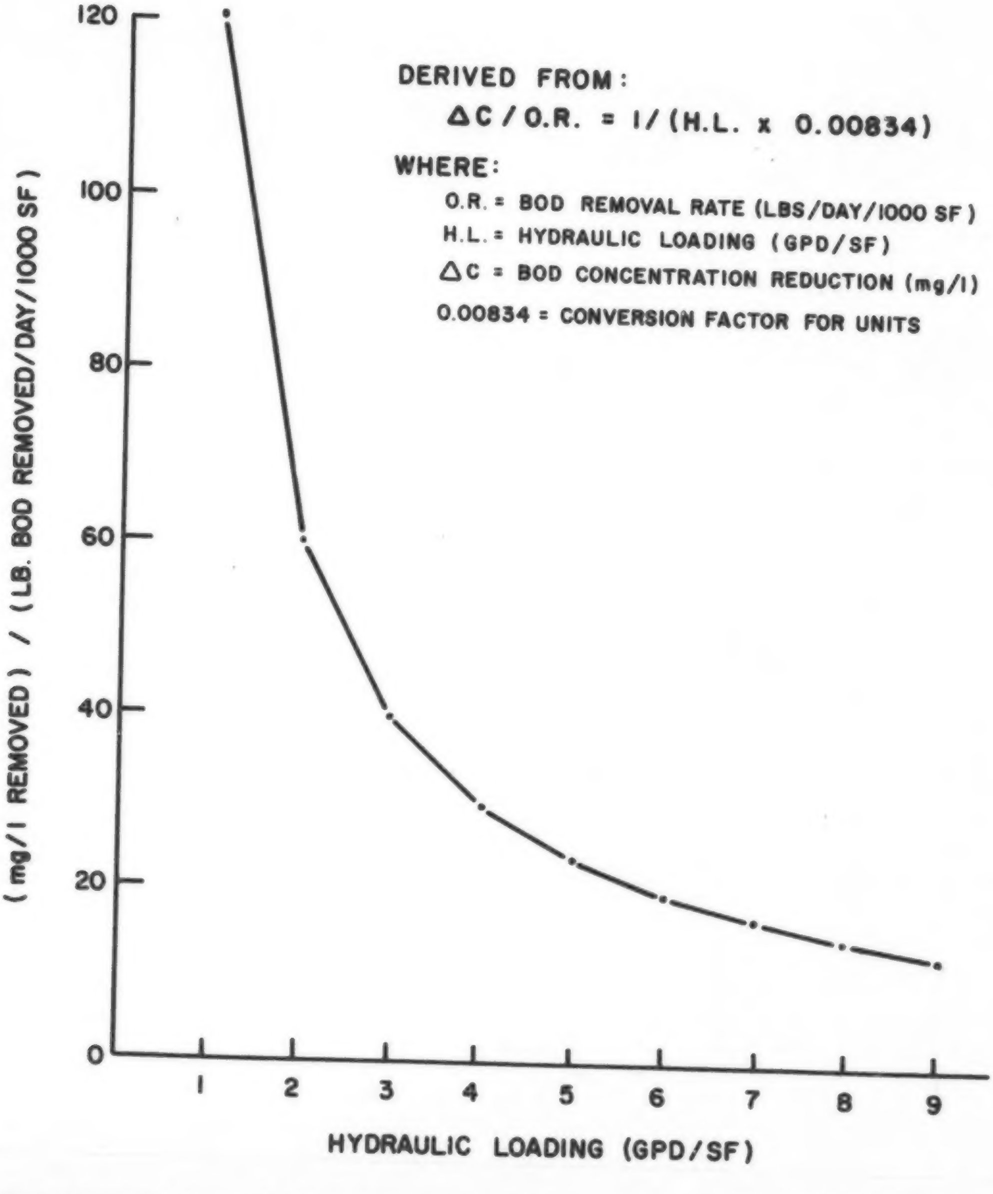


Figure 16. Influence of hydraulic loading and organic removal rate on changes in BOD concentration.

Design Versus Observed Performance --

Data generated in Figures 13, 14, and 15 were graphically compared to manufacturers' design guidelines. Manufacturers' design curves were constructed from design guides, converting SBOD to BOD using manufacturers' recommendations (2, 49).

A comparison of percent BOD removal versus hydraulic loading with manufacturers' design curves for the influent concentration ranges examined in Figure 13 is presented in Figure 17. A comparison of mass BOD removed versus hydraulic loading for the influent concentration ranges examined in Figure 14 is presented in Figure 18(a).

The manufacturers' design curves in both Figures 17 and 18(a) predict better performance than that which was observed in the 16 plants which were analyzed. Although the differences in Figure 18 appear to be minor, small differences in mass BOD removal rates result in large differences in effluent concentration as previously discussed and presented in Figure 16.

Figure 18(b) presents a comparison of mass BOD removed versus mass BOD loading. The manufacturers' design data are divided into design curves based on influent RBC concentration. The results are similar to the previous analyses in that the regression line depicts lower removal rates than those predicted by manufacturers' design guides.

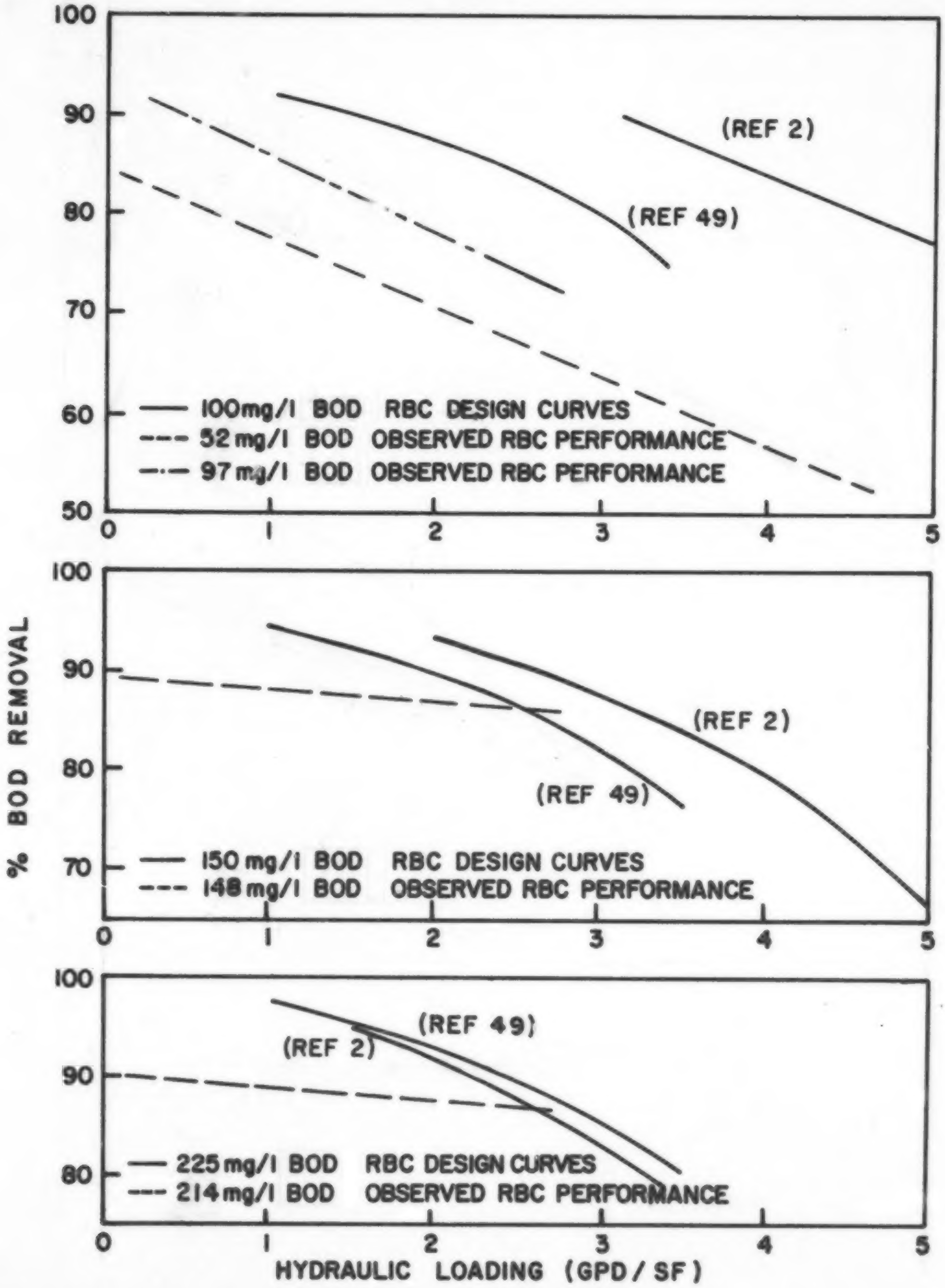
The conclusion from this analysis is that RBC performance was less than that predicted by manufacturers' design recommendations for average influent BOD concentrations ranging from 97 to 214 mg/L, with hydraulic loadings ranging from 0.5 to 3.0 gpd/sf. Some potential reasons for this include:

1. The absolute values of the manufacturers' curves are based on field data accumulated at specific locations which may not reflect RBC performance elsewhere.

2. Plant performance is the result of a series of unit processes. Poor secondary clarifier performance would adversely affect recorded RBC performance.

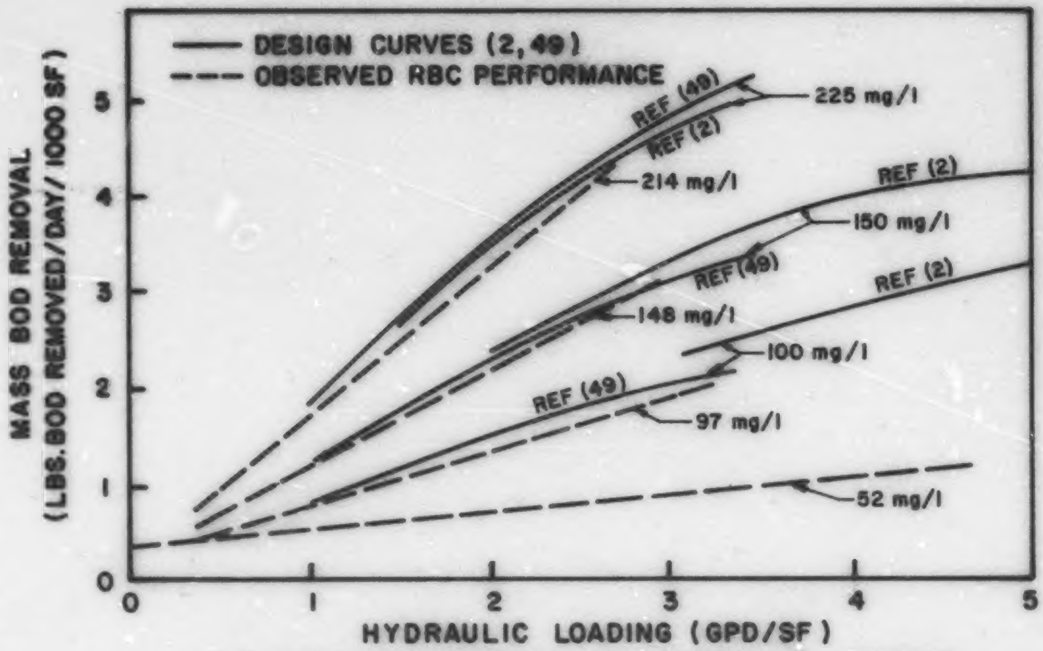
3. Operation and maintenance practices at specific plants influence overall plant performance which would reflect on RBC performance.

More than likely the manufacturers' design data reflect observed performance in facilities with optimum operating conditions which are not often encountered in most facilities. Some of the observed problems at the 16 facilities surveyed are presented in Table 11.

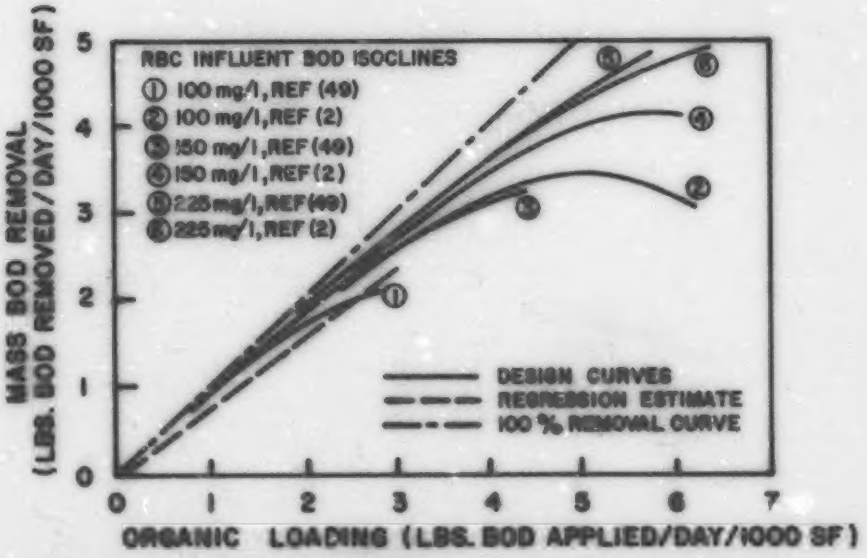


NOTE: BOD ISOCLINES REPRESENT RBC INFLUENT CONCENTRATION

Figure 17. Comparison of design curves to observed RBC performance (efficiency vs. hydraulic loading).



(a) MASS BOD REMOVAL VS. HYDRAULIC LOADING



(b) MASS BOD REMOVAL VS. ORGANIC LOADING

Figure 18. Comparison of design curves to observed RBC performance.

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Interstage Dissolved Oxygen Profiles --

Dissolved oxygen is a key performance parameter in RBC systems. Despite its role, little monitored data are available. As a result, interstage D.O. monitoring was undertaken at the six facilities visited.

Profiles of the results are presented in Figure 19. Dissolved oxygen profiles reflect the simultaneous activities of two processes: disc reaeration and biomass oxygen uptake. Reaeration can be supplemented by air drive systems (plant No. 16) or supplemental air supplied independently (plant No. 7). Otherwise, if disc rotation is constant the observed dissolved oxygen profile is dependent on the number of stages (i.e., detention time) and the influent organic concentration. The exact profile, however, is unique to the operating conditions at each plant, and is an excellent indicator of interstage process activities.

Plant No. 4 -- This plant was achieving very good removals (90 percent), although hydraulic and organic loadings were less than 10 percent of design at the time of the sampling. Reaeration was occurring in the first stage and an overall increase in D.O. of 2.8 mg/L was achieved through the four stages.

Plant No. 7 -- This is an organically overloaded plant, with dissolved oxygen limitations and nuisance organisms in the first stage, and with heavy growths throughout. Aeration is provided in the channels between shafts, which creates the step up in oxygen depicted in Figure 19.

Plant No. 13 -- High flow rates and low organic concentrations combine to provide high influent D.O. concentrations. Some organic removal is shifted to the second stage depressing D.O. concentrations, but there is enough surface area (and detention time) for the removal of carbonaceous material and for a subsequent rise in D.O. levels in the latter stages.

Plant No. 14 -- High flow rates at this plant help to create high influent D.O. concentrations; organic loading and removal is shifted and distributed from the initial stages to the latter stages of the system, resulting in a slow net oxygen uptake in each stage.

Plant No. 15 -- Nuisance organisms are present in the first stage shifting organic loads to subsequent stages. As a result, D.O. levels remain depressed through the second stage. As removal takes place, biological activity slows and reaeration begins to occur in the latter stages.

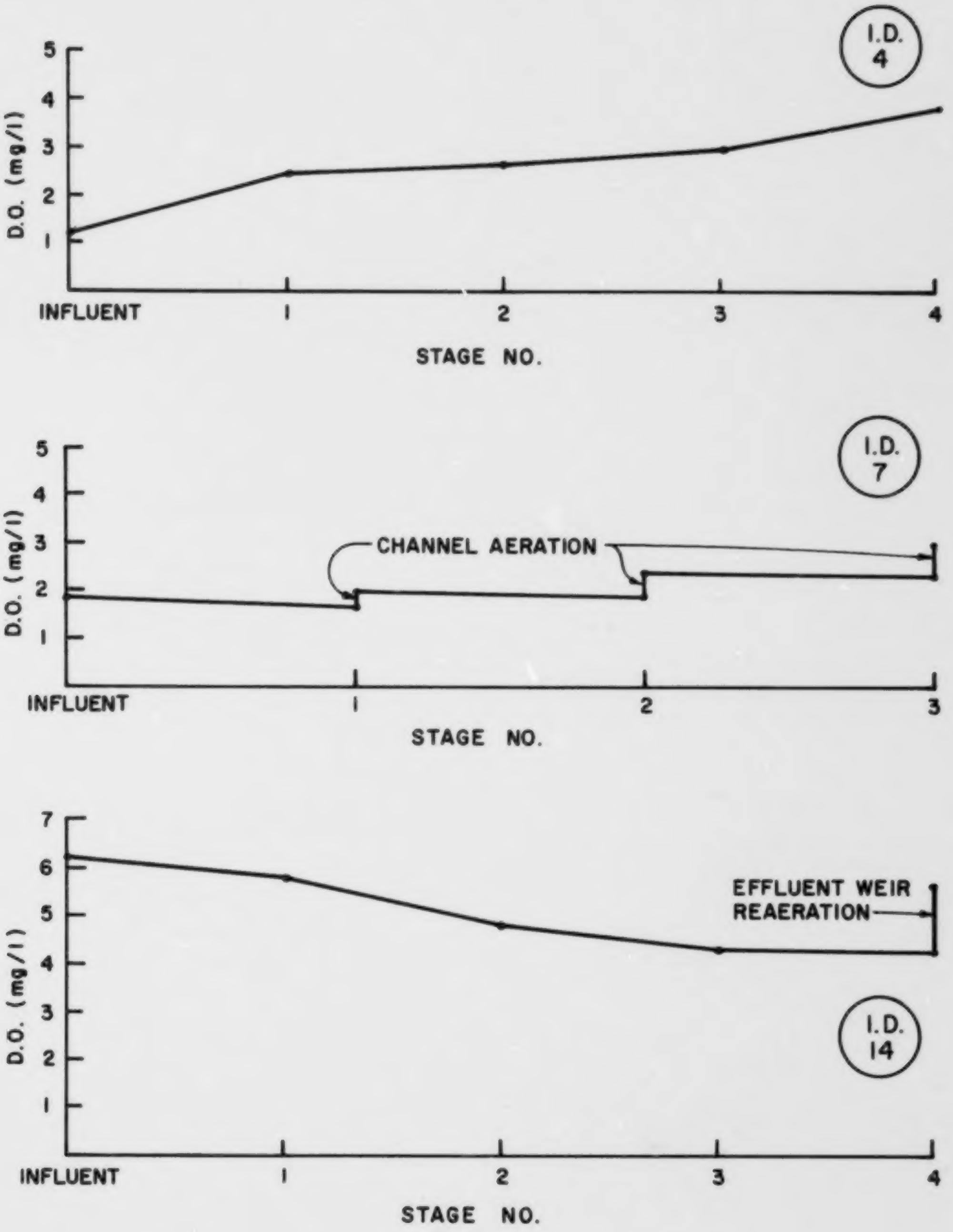

Figure 19. Dissolved oxygen profiles.

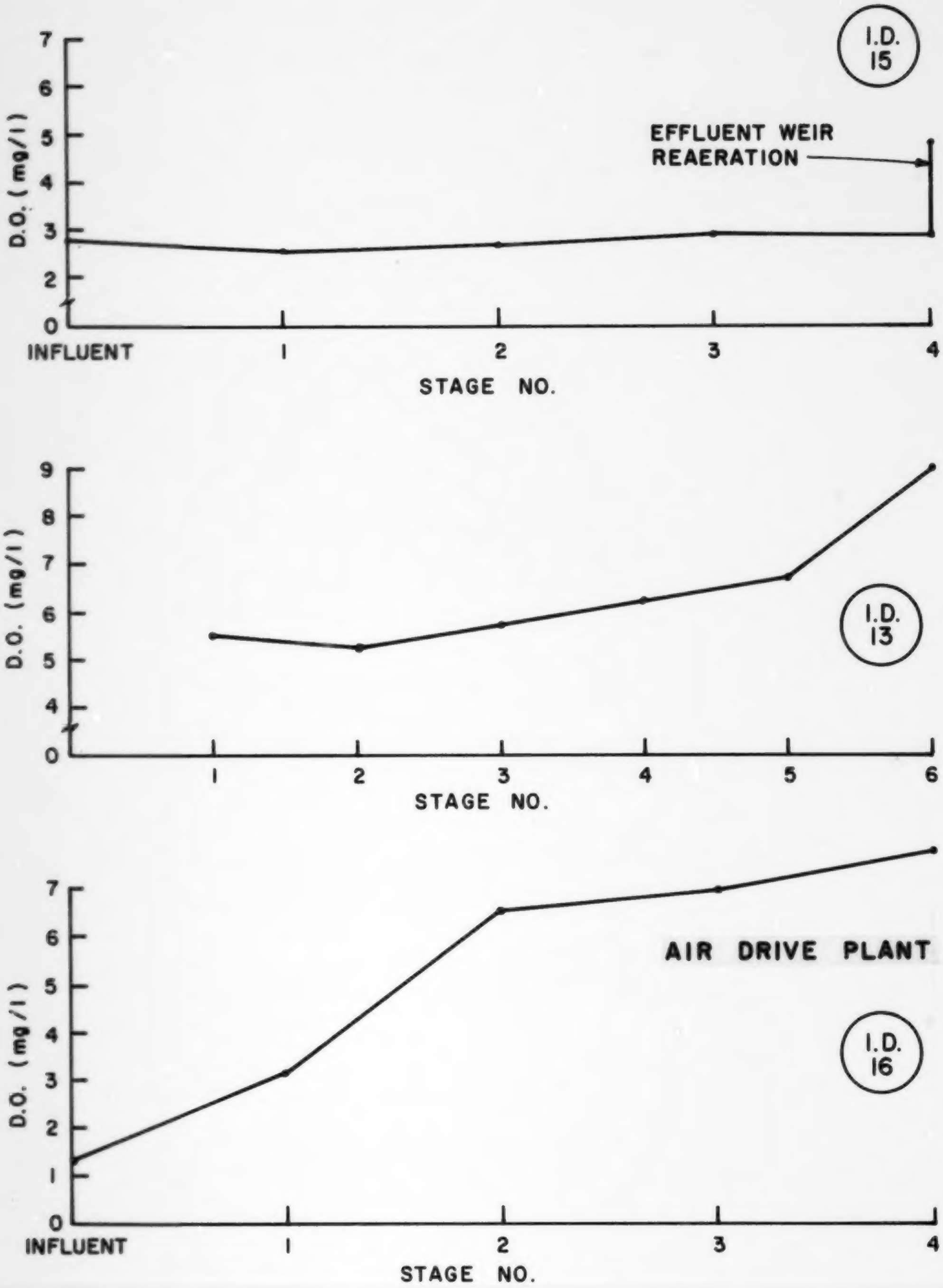

Figure 19. (continued).

Plant No. 16 -- This is an air drive plant where dissolved oxygen concentrations in the reactor can be controlled by increasing the air drive blowers. The observed results were a continuous increase in dissolved oxygen through the system.

EQUIPMENT REVIEW

Through 18 site visits and contact with six other facilities, a survey of structural problems encountered at RBC facilities was undertaken. Some failures which occurred are endemic to any mechanical system, and others are major and cannot be considered routine replacement. The equipment performance is broken up into three areas:

1. Shaft - includes the horizontal support, bearing axles, and bearings. In the case of structurally supported media, the radial arms are part of the shaft.
2. Media - the polyethylene sheets, formed into a variety of shapes, whose surface supports the growth of a biological film. They are either formed to support their own weight or are supported by steel arms radiating from a shaft.
3. Drive - includes the motor and the system which connects it to the shaft. These systems are generally cartridge type gear reducers, V-belts, or chain and sprocket.

Shaft Failures

The most serious equipment problem that can impact an RBC unit is a shaft failure. A shaft break entails the loss of the unit. Depending on the site layout, shaft removal may entail the removal of covers and building walls or the roof.

The number of shaft failures identified are listed in Table 13. Shaft failures are reported for seven of the 17 plants. None of the replacement shafts have been reported to fail. Of the 12 shaft failures reported, all but one were located in the first stage of treatment. Loadings on these units are the highest in the system. This strongly suggests that shaft failures are a result of increased weight of biological mass.

Bearings fail in RBC units when not properly maintained, when shaft deflections preceding failure cause undue stress on the bearings, and when broken seals allow corrosive wastewater onto bearing surfaces. Eight bearings in three plants have been replaced. Support arms are used by three out of four manufacturers. Previous designs were inadequate to support the media and units of this type have been replaced. Two of the 18 plants have replaced these members.

Media

Media failures can be due to either a failure of the plastic resulting from degradation due to exposure to heat, concentrated organic solvents, ultraviolet radiation, excessive weight resulting from heavy biomass growth, or calcium precipitation common with lime pretreatment. They may also fail if metal support members allow excessive movement. Six plants listed in Table 12 have reported trouble in this area, with corrective action ranging from simple bracing to replacement of the entire unit. Two additional facilities, not formally part of the survey, have recently experienced media problems.

Drive

The drive system is the most reliable mechanical component of an RBC system. Only three problems have been reported and these have been minor. Operating experience of the structural integrity of air drive systems is limited to the three-year history of plant No. 25, where neither process nor structural problems exist. During a site visit, growths were observed to be very heavy but there have been no difficulties with the equipment or the air drive system.

Table 13 presents the rate of failure of shafts, bearings, radial arms, media, and drive systems of the equipment surveyed in all of the 17 plants listed in Table 12.

TABLE 13. EQUIPMENT FAILURE RATE

Item	Number in survey	Number failed	Rate of failure percent	Average age at failure years
Shaft Break	141	20	14	2
Bearings	282	8	3	3
Radial Arms	23	7	30	5
Media	141	14	10	4
Drive Systems	141	9	6	6

TABLE 12. STRUCTURAL PERFORMANCE OF RBC PLANTS

			Record of failures											
			Shaft				Media				Drive			
Plant ID No.	No. of shafts	No. of years in operation	No. of failures	Description	Age at failure years	Corrective action	No. of failures	Description	Age at failure years	Corrective action	No. of failures	Description	Age at failure years	Corrective action
1	10	3	2	Shaft break	2	Replace	---	---	---	---	---	---	---	---
4	2	5	4	Radial arms deteriorating	1	Replace	1	Media shifting	1	Repair (tighten)	5	Broken drive chain	1	Repair
5	4	6	---	---	---	---	4	Hub failures	1	Replace	---	---	---	---
6	3	4	3	Radial arms deteriorating	3	Replace	1	Slight media shifting	3	None as yet	---	---	---	---
7	12	5	4	Seized bear-ings	3, 4	Repair (2) Replace (2)	1	Brittleness	4	None	---	---	---	---
9	4	4	2 2	Shaft break; worn bearings	2 2	Replace Replace	---	---	---	---	---	---	---	---
10	4	6	2 1	Worn bearing; shaft break	5 3	Replace Replace	---	---	---	---	---	---	---	---
11	2	2	---	---	---	---	---	---	---	---	---	---	---	---
12	4	5	3	Shaft break	4	Replace	---	---	---	---	---	---	---	---
13	6	6	---	---	---	---	---	---	---	---	---	---	---	---
14	8	1	1	Shaft break	1	Replace	---	---	---	---	---	---	---	---
15	12	3	8	Shaft break	3	Replace	1	Media shifting	1	Braced	2	Broken drive chain	1	Replace
16	2	2	---	---	---	---	---	---	---	---	---	---	---	---
17	6	2	2	Shaft break	1	Replace	6	Media breaking	1	Replace	---	---	---	---
19	48	1	1	Shaft break	1/2	Replace	---	---	---	---	---	---	---	---
25	6	3	---	---	---	---	---	---	---	---	---	---	---	---
28	8	9	---	---	---	---	---	---	---	---	1 1	Electrical drive chain	8 6	Repair Replace

SECTION 9

EVALUATION OF POWER REQUIREMENTS

INTRODUCTION: LITERATURE SEARCH

Power requirements in wastewater treatment systems can significantly impact the cost effectiveness of the process. Nonetheless, only limited published data concerning energy utilization in wastewater treatment facilities are available. Energy utilization in wastewater treatment systems is often defined by manufacturer's estimates of power requirements for their unit operation and not by actual metered records of full-scale operating plants.

Table 14 lists overall plant energy utilization reported in several references. Included in this listing is information collected in questionnaires sent to RBC facilities as part of this investigation. The results are presented in terms of average kwh per million gallons for the overall facility and for the biological process alone, as well as the range of kwh per million gallons reported and the sources of information. Except for pure oxygen activated sludge systems, all overall facility energy figures represent metered records at the plant. Figures for secondary treatment plant operation given in parenthesis represent unmetered estimates.

Energy consumption is reported in terms of energy per unit flow to normalize the facility size. This parameter, however, fails to account for facility performance or potential economies of scale. Data reported in this manner ranks wastewater treatment plants using RBC systems second to those using trickling filters in terms of potential energy requirements per unit wastewater volume.

RBC systems require energy for disc rotation. Commercially available systems rotate the discs by one of two methods: mechanical drive or air drive.

In order to assess the power required to drive RBC systems, 14 facilities were visited and power consumption monitored. Table 15 lists these facilities along with test date, type of drive, number of shafts, surface area, type of media, flow rate

TABLE 14. SECONDARY TREATMENT PLANT ENERGY USAGES COMPILED FROM REFERENCES AND SURVEY DATA

Process	No. of plants	Average kwh/MG	Range kwh/MG	Source
Trickling Filter	6	692	400 - 1,100	(59)
	1	(192)	---	(60)
RBC	2	1,550	720 - 4,072	(59)[1]
	5	(533)	(223 - 1,688	(59) (61) (62)[1]
Pure O_2 Activated Sludge	1	1,042	1,042 - 1,583	(60)
	1	(734)	(694 - 770)	(60)
Activated Bio-Filter	2	1,365	430 - 2,300	(59)
	1	(808)	---	(63)
Oxidation Ditch Extended Aeration	3	2,123	870 - 3,200	(59)
Conventional Activated Sludge	5	2,680	1,300 - 4,300	(59)
	2	(912)	(570 - 894)	(61) (64)
Activated Sludge Extended Aeration	5	3,460	2,700 - 4,300	(59)
Activated Sludge Contact Stabilization	2	3,950	2,100 - 5,800	(59)

NOTE: Data given in parenthesis is for secondary portion of treatment process only.

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[1] Roy F. Weston survey, plants No. 1, No. 13, and No. 14 (October 1979).

TYPING GUIDE SHEET

TABLE 15. TEST SITES FOR WESTON FIELD AUDITS OF RBC POWER UTILIZATION

Plant ID No.	Test date	Type of drive	Number of shafts			Surface area (1,000 sq ft)			Flow		RBC hydraulic loading		RBC equipment supplier
			Standard	High density	Total	Standard	High density	Total	Actual mgd	Design mgd	Actual mgd	Design mgd	
4	02-17-84	Mechanical	2	---	2	700	---	170	0.16[1]	0.20	0.94	1.18	Clow-Environdisc
6	02-16-84	Mechanical	3	---	3	300	---	300	0.63	0.30	2.10	1.00	Clow-Environdisc
7	02-17-84	Mechanical	12	---	12	1,200	---	1,200	1.19[1]	1.30	1.03	1.13	Autotrol
17	02-14-84	Mechanical	6	---	6	600	---	600	1.00[1]	1.17	1.57	1.75	Clow-Environdisc
18	02-14-84	Mechanical	4	2	6	400	300	700	2.20[1]	2.70	3.14	3.86	Autotrol
19	02-14-84	Mechanical	24	24	48	2,400	3,600	6,000	10.00[1]	10.00	1.67	1.67	Autotrol
20	02-17-84	Mechanical	3	---	3	210	---	300	0.05[1]	0.50	0.17	1.67	Tait/Bio-Shaft
26	02-22-84	Air	2	2	4[2]	192	284	476	0.20	0.50	0.42	1.05	Autotrol

[1] Based on earlier observations.
[2] Three shafts in operation.

(design and actual), hydraulic loading, and equipment supplier. Seven of the facilities tested were mechanical drive systems and seven were air drive systems. Results are presented later in this section.

PARAMETERS INFLUENCING RBC POWER CONSUMPTION

RBC systems require energy to overcome the frictional drag forces associated with rotation of the discs through the wastewater. The magnitude of the drag force is a function of the total surface area, surface characteristics of the discs, viscosity of the wastewater, and rotational speed. The drag is related to shear forces created between the surface of the film and the adjacent layer of wastewater.

Surface area affects the drag force which must be overcome for rotation. The nature of the disc surface, which is influenced by the type of biomass growth, affects the drag; smoother biomass growth is less resistant than shaggy growth.

Viscosity introduces resistance to motion by causing shear or frictional forces between fluid particles and the biomass. Work must be done against this resistance. Viscosity is dependent on wastewater temperatures decreasing with increasing temperatures.

Previous studies (50) on mechanical drive units have reported power as a function of the cubic power of rotational velocity. This relationship would make rotational speed the most sensitive parameter affecting power consumption in RBC systems. Mechanical drive systems must overcome the internal resistance of the motor, the gear reduction box, and the drive shaft in addition to the forces on the disc surface.

Air drive systems must overcome the internal resistance of compressors, headers, and diffusers and energy losses associated with the conversion of diffused air bubbled through the liquid in the RBC reactor into mechanical energy.

PREVIOUS INVESTIGATIONS

Clean Media Tests

A number of power tests on mechanical drive systems were undertaken by RBC manufacturers in 1978 on clean media without biofilm growth. Table 16 lists the respective sponsor of the test, the date, location, description of the test unit, and the power consumption in kw. The results indicate a relationship which is dependent on surface area, rotational velocity, temperature, and manufacturer.

TABLE 16. MANUFACTURERS' POWER TESTS ON CLEAN MEDIA

				Physical Description of Test Unit							
					Media						
Manufacturer	Reference	Date of test	Location	Motor hp	Surface areas sq ft	Standard density	High density	Wastewater temperature °F	Rotational speed rpm	Reporter power consumption kw	Reporter power consumption watts/sq ft
Clow-Envirodisc	(50)	April 1978	Baldwin Place, NY	3	33,000	X		N/A	1.67	0.82	0.0248
				3	33,000	X		N/A	1.40	0.54	0.0164
	(57)	Nov. 1978	Plainville, CT	7-1/2*	100,000	X		52	1.43	1.36	0.0136
				7-1/2	100,000	X		52	1.42	1.52	0.0152
				7-1/2	150,000		X	52	1.43	1.94	0.0129
				7-1/2	150,000		X	52	1.38	1.72	0.0115
Autotrol Corporation	(58)	Oct. 1978	Princeton, IL	5	100,000	X		58	1.72	1.16	0.0116
				5	100,000	X		58	1.74	1.24	0.0124
				5	152,000		X	58	1.73	1.67	0.0110
				5	152,000		X	58	1.70	1.48	0.0097

*High efficiency motor.

For units tested by the same sponsors and operated at similar rotational velocities, the relationship between power (P) and surface area (A) was approximately linear (i.e., $P_1/A_1 = P_2/A_2$). For example, systems tested by Clow with rotational velocities between 1.38 and 1.43 rpm and surface areas between 100,000 and 150,000 square feet had relatively consistent P/A ratios (watts/square feet) ranging from 0.0115 to 0.0136. The unit tested by Autotrol with rotational velocities from 1.70 to 1.74 has P/A ratios ranging from 0.0097 to 0.0124.

Clean water tests conducted at Baldwin Place, New York (50) on a mechanical drive unit included detailed analysis of power requirements at different rotational velocities and surface areas. The unit tested was composed of a four-stage 12-foot shaft, with a total of 33,000 square feet of standard media on the 12-foot diameter discs. Each stage, consisting of 8,250 square feet, was individually tested for power consumption at various rotational velocities by consecutively including stages on the shaft. A summary of power test conditions are listed in Table 17 and include motor alone, motor plus gear reduction box, motor plus gear box and shaft, and each stage consecutively. Disc rotational velocity at each test condition was varied between 0.5 and 2.25 rpm.

Overall results are presented in Figure 20, which displays power consumption as a function of rotational velocity (N) for the various test conditions defined in Table 17. Relationships between power and rotational velocity are defined for each test condition. The results suggest a cubic relationship between power and rotational velocity. The additional $N^{1.3}$ term defines power requirements needed to overcome the internal resistances associated with driving the motor and gear box. This term becomes less significant as the surface area increases.

Relationships between power and surface area for a constant 1.6 rpm are presented in Figure 21. The results indicate a linear relationship between power and surface area. As a result, power as a function of surface area can be approximated by the relationship:

$$P = m A + b$$

where P = power consumption (kw)
A = surface area (1,000 sf)
b = power consumption required to drive the motor gear box and shaft with zero surface area (kw)
m = slope of linear relationship (kw/1,000 sf)

TABLE 17. BALDWIN PLACE POWER TEST CONDITIONS (50) CLOW ENVIRODISC UNIT, STANDARD MEDIA

Test No.	Motor	Gear box	Shaft	Media stage number 1	2	3	4	Description of equipment tested
1	X							Motor Draw Only
2	X	X						Motor and Gear Box
3	X	X	X					Motor, Gear Box, and Shaft
4	X	X	X	X				One Stage Plus Motor, Gear Box, and Shaft
5	X	X	X	X	X			Two Stages Plus Motor, Gear Box, and Shaft
6	X	X	X	X	X	X		Three Stages Plus Motor, Gear Box, and Shaft
7	X	X	X	X	X	X	X	Four Stages Plus Motor, Gear Box, and Shaft

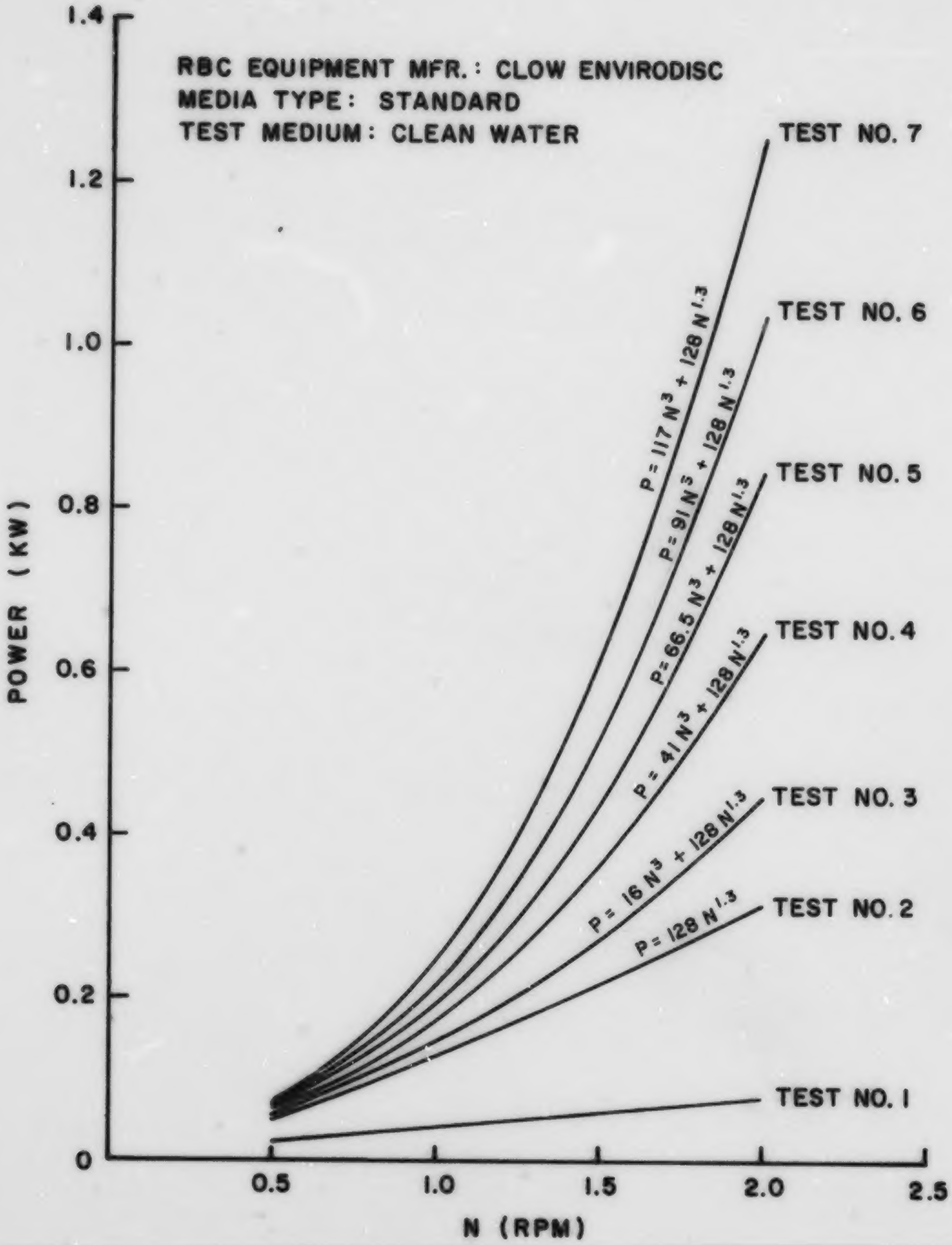

Figure 20. Power vs. rotational speed, Baldwin Place, New York.

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(20)

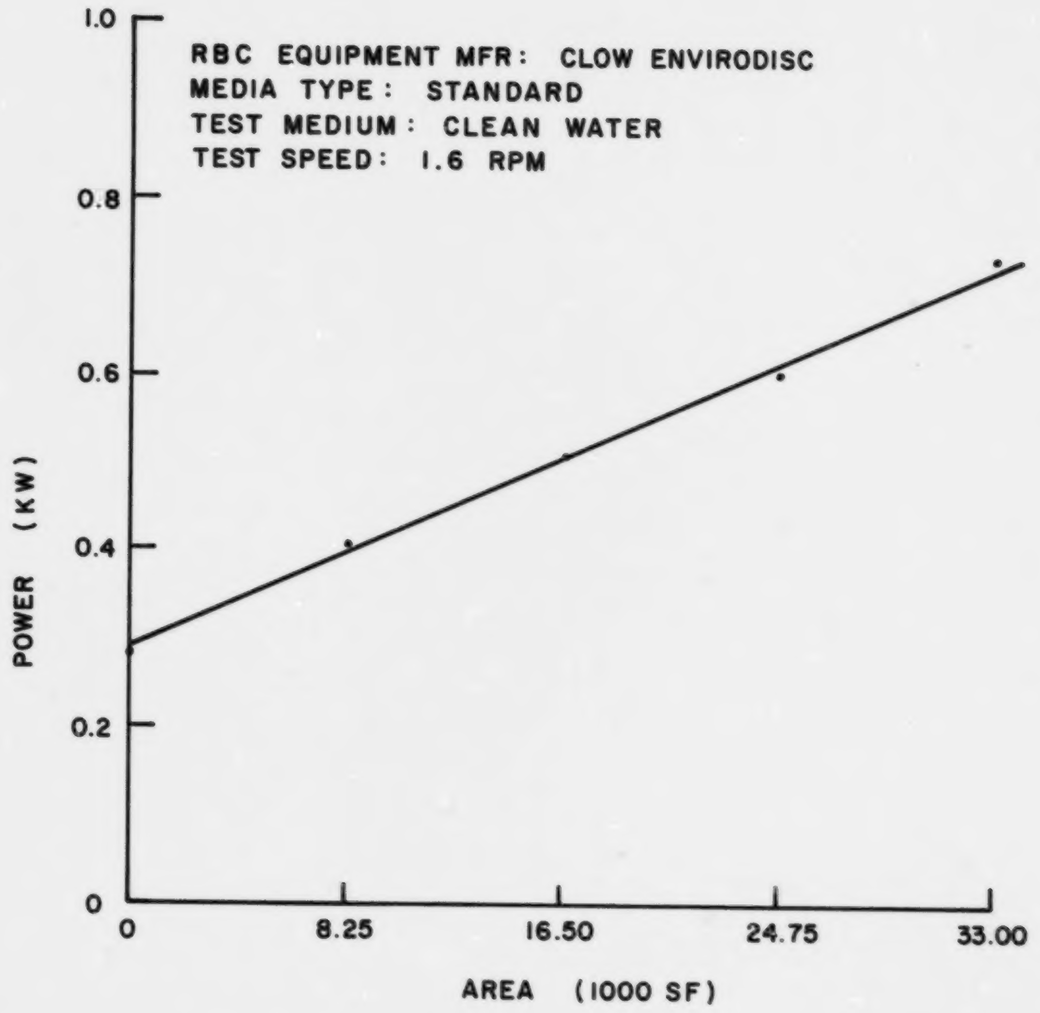

Figure 21. Power vs. surface area, Baldwin Place, New York.

As the total surface area increases, the impact of b becomes smaller and, for practical purposes, power can be assumed to be directly proportional to surface area (i.e., $P_1/A_1 = P_2/A_2$).

Operating Facility Tests

Two previous field investigations have been reported for plant No. 15 (65) and plant No. 13 (66). The results are presented for each test in Tables 18 and 19.

At plant No. 15, actual power use at the plant was measured by utility company meters recording the power consumption of each RBC motor. The RBC portion of the plant consists of two parallel flow paths (a third is left idle), labelled A and B in Table 18 of four, 12-foot diameter RBC units each. Each shaft supports 100,000 sf of media. The first stage of each flow path is colonized by nuisance organism growths (Beggiotoa; see Section 4). The growth is thicker than the normal 1/8" brown shaggy biofilm found downstream and is smooth and glossy in appearance. Power consumption per shaft, listed in Table 18, averaged 3.35 kw with a shaft speed of 1.6 rpm.

At plant No. 13 power requirements for a 12-foot diameter, 70,000 square foot shaft rotating at 1.6 rpm averaged 3.12 kw. With decreasing growth observed in the latter stages of the plant, it was concluded (65) that the initial stages of media with thicker growths consume more power than the latter stages with thinner growths.

The rate of energy consumption presented in Tables 18 and 19 is significantly higher than the power use reported in Manufacturers Clean Water Tests (Table 16). One reason for this is the increased drag and friction forces induced in the operating plants by the biomass adhering to the media, additional forces that are not factors in clean water tests.

CURRENT INVESTIGATION

Survey Methodology

Eight facilities were visited and tested for power consumption (Table 15). The test procedure consisted of installing in the power circuit of an RBC motor a precalibrated power usage meter. The instrument used was the Esterline Angus Power Master III AC Multimeter. Electrical parameters measured were volts, amps, kw, kva, and power factor. Maximum and minimum values were observed for each parameter.

TABLE 18. AVERAGE RBC POWER USE (kw) AT PLANT NO. 15

12-foot Diameter Units Rotating at 1.6 rpm
Under Field Loaded Conditions

Stage[1]	Media area per stage 1,000 sf	Power (kW) Parallel flow paths A	B
1	100	3.23	3.25
2	100	3.67	3.53
3	100	3.46	3.36
4	100	3.23	3.03

$$\frac{\text{Average Power Use (kw)}^1}{\text{Shaft}} = 3.35$$

TABLE 19. AVERAGE RBC POWER USE (kw) AT PLANT NO. 13

12-foot Diameter Units Rotating at 1.6 rpm
Under Field Loaded Conditions

Stage[2]	Media area per stage 1,000 sf	Power (kW) Parallel flow paths A	B
1 and 2	35	3.70	4.18
3 and 4	35	2.80	2.76
5 and 6	35	2.61	2.68

$$\frac{\text{Average Power Use (kw)}^2}{\text{Shaft}} = 3.12$$

---

[1] Stages 1 through 4 are each single 100,000 sq ft shafts.
[2] Stages 1 through 6 are 35,000 sq ft each.

The wattmeter reads true power input, properly compensating for values of both current and voltage from zero up to the capacity of the instrument and on AC for changes in the power factor (67). Since power factor is typically low (< 0.7) for wastewater treatment plants, it is important that power measurements account for power factor to give proper assessment of power consumption. The use of a wattmeter has previously been recommended in determining the transfer efficiency of aerators for much the same reasons described above (68).

For mechanically driven units, the instrument measured the kw draw of each motor driving one shaft. In an air drive plant, air is compressed by one or two motor/blower combinations and used to drive from two to eight separate shafts. A single shaft could not be tested in an air drive plant. If the air headers to all but one of the Aero-Surf shafts were closed, several factors would invalidate the reading. First, the unit now driving only a fraction of its original load is oversized for the task. Second, throttling on this scale would increase line pressure significantly, in turn increasing the temperature of the compressed air. This heat loss is a loss in energy and results in a lesser efficiency than under true operating conditions. Third, the speed of the moving shaft would be hard to maintain at the original level.

Test Results

Mechanical Drive --

In a mechanical drive RBC plant, each motor drives only one disc shaft. Rated at 5 to 7.5 hp, motors are connected to the shaft via a speed reducer or gear reduction box. Motor speeds averaged 1,200 rpm and were converted to RBC rotational speeds ranging from 1.46 to 1.6 rpm. Seven mechanical drive plants were visited and a total of 23 motor/shaft units were tested.

The parameters given for each unit tested in Table 20, such as stage number, surface area, etc., all affect the rate of energy consumption. From the previous data analysis the major factors affecting power consumption were judged to be rotational speed and media surface area. The influence of the remaining parameters are assumed minimal in comparison and may be disregarded.

Results of the metering program for standard media in the seven plants are listed as kilowatts in Table 20 under the column headed "Observed Power Consumption." Corrections to normalize power readings for media area and rotational speed may be undertaken by use of the relationships developed by others and described prior to this under the subsection Previous Investigations.

Resultant average power consumption for 100,000 square feet of 12-foot diameter standard media discs (uncorrected for speed) was calculated at 2.29 kw or 3.07 hp. These tests also verified the higher power required for the heavier loaded shafts.

Table 21 presents the results of the high density media measurements at plant No. 19. No surface area adjustment was necessary for high density media. All high density shafts measured had a surface area of 150,000 square feet. The average power consumption of 150,000 square feet of high density media (uncorrected for speed) was computed to be 3.39 kw or 4.54 hp per mechanically driven shaft.

TABLE 20. FIELD POWER MEASUREMENTS: MECHANICALLY DRIVEN RBC UNITS/STANDARD MEDIA

Plant ID No.	Stage	Motor rating hp	Bio mass[1]	Surface area sq ft	Rotational speed rpm	Observed power consumption[2] kw
4	1st	7-1/2	B	85,000	1.5	2.55
	2nd	7-1/2	B	85,000	1.5	2.75
6	1st to 4th	5	B	70,000	1.5	1.65
	1st to 4th	5	B	70,000	1.5	1.7
	1st to 4th	5	A	70,000	1.46	2.0
7	12th	7-1/2	B	100,000	1.54	2.45
	11th	7-1/2	B	100,000	1.54	2.5
	10th	7-1/2	B	100,000	1.58	2.15
17	3rd	7-1/2	C	100,000	1.55	3.05
	4th	7-1/2	C	100,000	1.55	---
	5th	7-1/2	C	100,000	1.55	3.25
18	4th	7-1/2	A	100,000	1.67	2.5
	5th	7-1/2	A	100,000	1.67	1.8
	6th	7-1/2	A	100,000	1.67	1.85
19	D-5	7-1/2	---	100,000	1.5 - 1.6	1.75
	E-6	7-1/2	---	100,000	1.5 - 1.6	1.8
	B-7	7-1/2	---	100,000	1.5 - 1.6	1.5
	B-8	7-1/2	---	100,000	1.5 - 1.6	1.5
20	1st to 4th	5	B	70,000	1.58	0.9

[1] Code A: Light
Code B: Normal
Code C: Heavy
Code D: Heavy and Beggiatoa

[2] Maximum and minimum readings averaged.

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TABLE 21. FIELD POWER MEASUREMENTS: MECHANICALLY DRIVEN RBC UNITS/HIGH DENSITY MEDIA

Plant ID No.	Stage	Motor rating hp	Surface area sq ft	Rotational speed rpm	Observed power consumption[1] kw
19	A-1	7-1/2	150,000	1.5 - 1.6	3.4
	A-2	7-1/2	150,000	1.5 - 1.6	4.6
	C-3	7-1/2	150,000	1.5 - 1.6	3.15
	C-4	7-1/2	150,000	1.5 - 1.6	2.4

[1] Maximum and minimum readings averaged.

Air Drive --

Compressed air, caught in air cups attached to the edge of the discs, causes disc rotation in air drive plants. A blower motor at plant No. 26 was metered for its power use. For reasons explained previously, air drive shafts could not be tested individually. Power consumption metered at the plant is listed in Table 22.

The data necessary to develop relationships between power and speed, and power and surface area of RBC units were not available for air drive systems. The previously described cubic relationship for speed and linear relationship for surface area were developed for mechanical drive systems and cannot be extrapolated for air drive power use. This is due to factors such as diffuser and pipe network headlosses and motor and blower efficiencies which play an undetermined role. As a result, power usage was not normalized for air drive and is reported in Table 22 as it was observed. The same table presents the power use per shaft (4.0 kw).

Comparison of Manufacturer Power Estimates With Field Evaluations

Estimates of power requirements provided by RBC manufacturers and reported in the literature were compared with those computed from field observations. The results are presented in Table 23.

TABLE 22. FIELD POWER MEASUREMENTS: AIR DRIVE RBC UNITS

Plant ID No.	Motor rating hp	Surface area (x 1,000 sq ft)			Bio mass[1]	Rotational speed rpm	Observed power consumption kw	Power consumption per shaft kw	Power consumption per 100,000 sf kw
		Standard	High density	Total					
26	15	192	142	334	C	1.20	12.0	4.0	3.6

[1] Code A: Light
Code B: Normal
Code C: Heavy
Code D: Heavy and *Beggiatoa*

TABLE 23. MANUFACTURER POWER ESTIMATES AND FIELD EVALUATIONS

Manufacturer	Power requirements (kw) Standard media	High-density media
Autotrol	2	3
Clow	2.4	2.6
Hormel	2.3	2.6
Walker	2.5	3.1
Average Field Evaluations	2.3	3.4

SECTION 10

PROCESS DESIGN GUIDELINES

INTRODUCTION

Empirical approaches proposed by RBC equipment suppliers are presently used almost exclusively by engineers for RBC municipal wastewater treatment design. The empirical approaches are simple to use and require the input of just flow rate, organic concentration (BOD or SBOD),[1] and removal efficiency to determine RBC surface area. They are limited in that the design methodology does not have a fundamental basis which accounts for organic removal, oxygen limitations, staging requirements (both number and size of stages) and changes in influent feed distribution such as step feeding and recycling. These design methods, proposed by various suppliers, are based on testing at a limited number of facilities.[2]

More rational fundamental approaches which utilize stagewise kinetic parameters and attempt to account for mass transfer, substrate and dissolved oxygen utilization, and changes in RBC physical configurations have been formulated, but have not been adequately demonstrated. These fundamental approaches are limited by their complex relationships which discourage their use by designers and by the difficulty in establishing true input parameters to these test models.[3]

On the basis of a review of available design methodologies, it is apparent that a simplified rational approach is desirable to define RBC performance. Nonetheless, during the course of this investigation, no simplified approach was found to be completely acceptable. The major difficulty rests with the inability to account, in a simplified manner, for the heterogenous nature of fixed film systems in which the mass transfer and utilization kinetics of substrate and oxygen must be defined. This problem is analagous to the difficulty in defining rational trickling filter design methodologies. Trickling film designs still rely on empirical and semi-empirical methodologies such as the Velz (74), Shulze (75), Eckenfelder (76), and Galler Gotaas (77) equations to account for the complex mass transfer and substrate removal mechanisms occurring in the trickling filter.

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[1] BOD refers to total 5-day BOD; SBOD refers to soluble 5-day BOD.

[2] See Section 7 for more detailed discussion.

[3] See Section 4 for more detailed discussion.

In the RBC process, reported difficulties resulting from organic overloads and dissolved oxygen deficiencies[1] have underscored the need to address oxygen limitations as well as substrate removal in RBC design. Given the complexity of models which attempt to address mechanisms for both oxygen and substrate transport and utilization an alternative two-step approach to RBC design is suggested.

1. Define and avoid the conditions which induce dissolved oxygen limitations.

2. Utilize a design methodology which can accurately define substrate removal kinetics which occur when oxygen is not a limitation.

The remainder of Section 10 describes the approach taken to provide data which can be used to address the above items. The results present data which successfully identifies conditions judged to induce organic overloading. A calibrated model is presented which demonstrates a rational approach to RBC design, but which is limited to low ranges of influent BOD concentrations. Finally, Section 10 presents some suggested guidelines relative to RBC design.

DISSOLVED OXYGEN LIMITATIONS

For the purposes of this discussion, oxygen limitations and organic overloading are used as equivalent concepts. Several methods have been recommended for identifying dissolved oxygen-limiting conditions in fixed film and RBC systems. Utilizing their proposed fixed film model, Williamson and McCarty (3) predicted that limiting conditions are capable of occurring at soluble BOD (SBOD) concentrations of 40 mg/L, adjacent to the biofilm. This would correspond to a mixed liquor RBC reactor concentration somewhat greater than 40 mg/L SBOD.[2] Autotrol Corporation (2) recommends a limitation based on an influent SBOD organic loading for mechanical drive systems of 4.0 pounds/

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[1] See Section 4 for more detailed discussion.

[2] The concentration gradient between the biofilm and the reactor is such that the reactor concentration is greater than the biofilm concentration (Figure 2).

day/1,000 sf. Field observations were made during the course of this investigation to define influent conditions which resulted in organic overloading. Overloaded environments were identified by their characteristic takeover by nuisance organisms which occur under oxygen deficient conditions.[1] For each of the facilities surveyed, information concerning nuisance organisms, influent organic concentrations, and hydraulic loading were recorded to determine the wastewater characteristics which could be associated with these conditions. The survey included a total of 23 facilities. Results are presented in Table 24.

A graphical presentation of these results is presented in Figure 22, which depicts a plot of total influent BOD on the ordinate and first-stage hydraulic loading on the abscissa. The graph presents an organic loading demarcation curve that separates facilities which experienced first-stage D.O.-limiting problems from those which did not (identified by the presence or absence of nuisance organisms).

The relationship is depicted as a hyperbolic function, which can be defined by the product of the ordinate and abscissa:

(BOD) (Hydraulic Loading) = Constant Organic Loading

The graph shows that an organic loading of 6.4 lbs BOD/day/1,000 sf represents the level at which overloading occurs. This organic loading is recommended as the maximum loading which should be applied to any RBC stage.

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[1] See Section 4 for more detailed discussion.

TABLE 24. CHARACTERISTICS OF FACILITIES SURVEYED FOR ORGANIC OVERLOADING CONDITIONS

Plant ID No.[1]	Average RBC influent BOD concentration mg/L	Average first stage hydraulic loading gpd/sf	Calculated average first stage organic loading lbs/day/1,000 sf	D.O.-limited[3] condition
1	145	10.3	12.4	P
2	96[2]	3.7	3.0	A
4	71[2]	1.7	1.0	A
5	150	7.7	9.6	P
8	52[2]	15.5	6.7	A
10	175[2]	7.0	10.2	P
12	80	17.9	12.0	P
13	80	3.8	2.5	A
14	71	13.1	7.8	A
15	167	8.8	12.3	P
16	61	7.2	3.6	A
29	93	18.5	14.4	P
30	175	5.8	8.4	P
31	145	6.3	7.6	P
32	505	1.9	8.1	P
33	350	3.9	11.3	P
34	94	6.4	5.0	P
35	175[2]	7.2	10.5	P
3	91[2]	11.6	8.8	A
6	152	4.8	6.0	A
9	144	7.9	9.4	P
11	82	11.6	8.0	P
36	212	6.6	11.6	P
7	228	3.1	5.9	P

[1] Except for air driven plant No. 16, all are mechanical drive facilities with no supplemental air.

[2] Assuming primary clarifier BOD removal at 25 percent.

[3] A: Plants experiencing no nuisance organism growth (absence) in the first stage.
P: Plants experiencing problems with nuisance organism growths in the first stage.

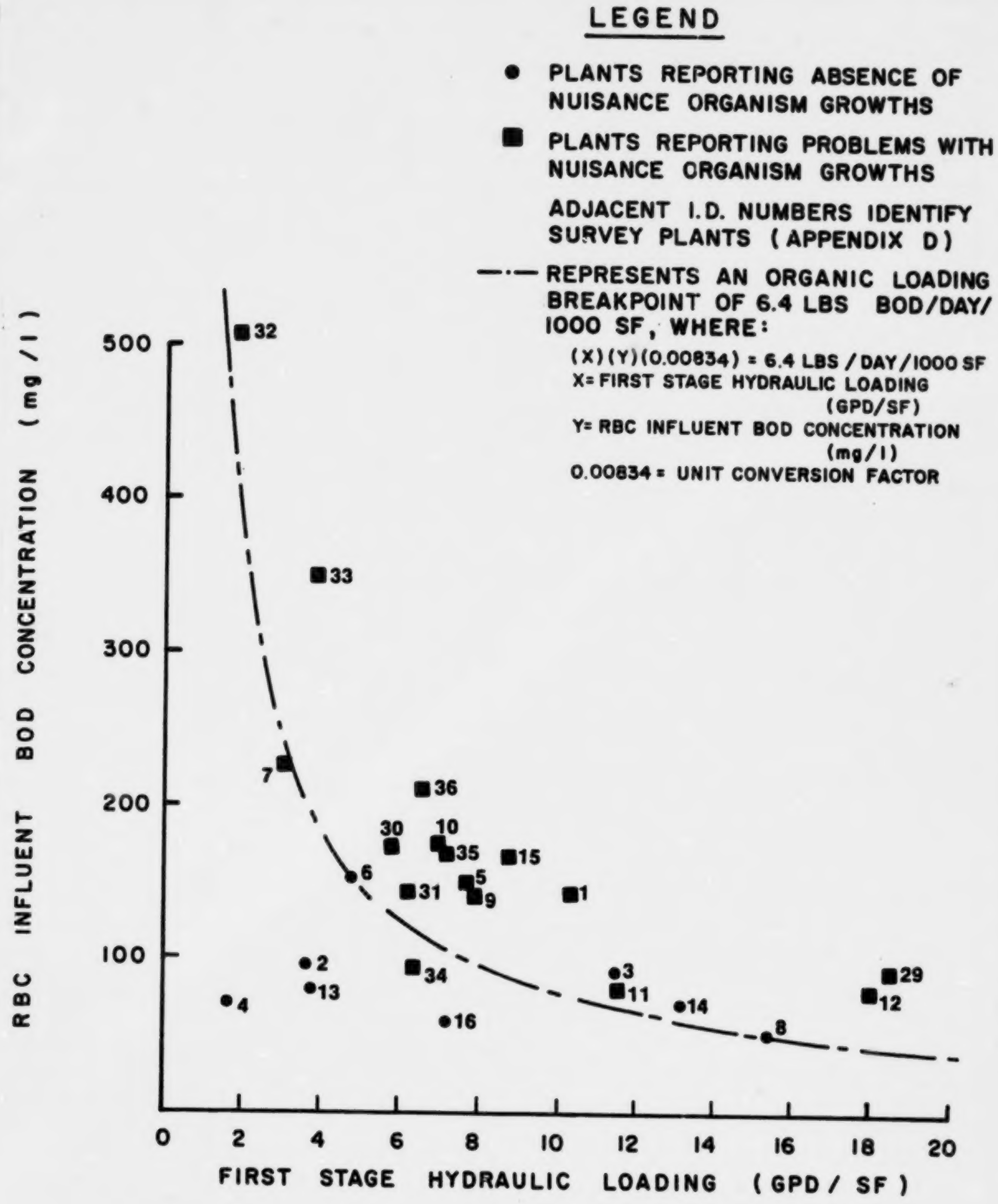

Figure 22. D.O. limiting conditions related to influent organic concentration and hydraulic loading.

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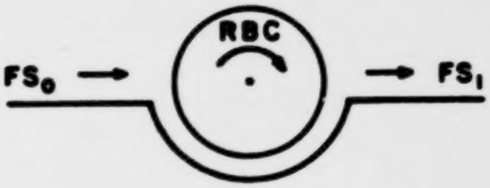
SUBSTRATE UTILIZATION MODEL

The approach described by Clark, et al. (7) is one rational approach to RBC design which defines interstage removal on the basis of Monod growth kinetics. The model is based on a mass balance with respect to substrate across an assumed completely mixed RBC stage at steady-state as follows:



$$V\left(\frac{dS}{dt}\right) = FS_o - FS_1 - \left(\frac{\mu}{Y} X A\right) \qquad (5)$$

where,

V = reactor liquid volume (L^3)

$\frac{dS}{dt}$ = change of substrate concentration with time ($\frac{M}{L^3}/T$)

F = wastewater flow rate (L^3/T)

S_o = influent organic concentration (M/L^3)

S_1 = effluent organic concentration (M/L^3)

= specific growth rate of attached RBC microorganisms (I/T)

Y = apparent yield of attached RBC microorganisms

$$\frac{\text{mass biomass produced}}{\text{mass substrate consumed}}$$

X = mass of attached microorganisms per unit area (M/L^2)

A = RBC surface area (L^2)

This equation assumes that the intensity of mixing in each stage is sufficient for complete mixing, that organism decay is small compared to the growth rate, and that all substrate removal is due to attached biomass.

Using the Monod growth function:

$$\mu = \mu_{max} \left(\frac{S_1}{K_s + S_1} \right) \qquad (6)$$

where,

μ_{max} = maximum specific growth rate of attached RBC microorganisms (I/T)

K_s = the Monod half-velocity coefficient (mass/volume)

Substituting in Eq. 6:

$$V\left(\frac{dS}{dt}\right) = FS_o - FS_1 - \left[\frac{\mu_{max}}{Y} A\, X\left(\frac{S_1}{K_s + S_1}\right)\right] \qquad (7)$$

defining,

$P = \frac{\mu_{max}}{Y} X$, as the area capacity constant (i.e., maximum substrate which could be removed per unit area per unit time) (8)

and,

$R = F(S_o - S_1)/A$, as the removal coefficient (actual substrate removed per unit area per unit time) (9)

then at steady-state where $V\left(\frac{dS}{dt}\right) = 0$, substituting Eq. 8 and 9 in Eq. 7 yields:

$$R = \frac{PS_1}{K_s + S_1}, \text{ or} \qquad (10)$$

$$\frac{1}{R} = \left(\frac{K_s}{P}\right)\left(\frac{1}{S_1}\right) + \frac{1}{P} \qquad (11)$$

Equation 10 relates organic removal rate per unit area, R, to a maximum removal rate, P, a half-velocity coefficient, K_s, and the equilibrium BOD concentration in a given completely mixed stage, S_1. Equations 10 and 11 are graphically displayed in Figures 23 and 24, respectively. Graphical determination of P and K_s can be made with the use of Figures 25 and 26. The determination of P and K_s permits the calculation or graphical determination of R (Figure 27) which defines BOD removal by the attached biomass in each stage.

A major feature of the Clark model is its use of a rational approach for defining substrate removal and converting the model terminology into design parameters which are readily used in the field today: R, the removal coefficient which reflects the organic removal rate, can be defined in terms of lbs/day/1,000 sf, and P, the area capacity constant, which represents the maximum removal rate possible, can also be described in terms of lbs/day/1,000 sf.

The Clark model, however, simplifies the kinetics of the RBC process by combining the effects of substrate and oxygen transport through the biofilm, and substrate and oxygen removal and reaction kinetics into one overall specific growth rate (u) and apparent yield (Y). P and K_s values, which are dependent on u and Y, reflect the biochemical reaction rates found in each stage of an RBC system. Since substrate transport can be a controlling factor in fixed film systems and since substrate transport is concentration dependent, values of P and K_s derived at a given concentration may not reflect P and K_s values at other concentrations. This would be expected where substrate transport is the rate-limiting condition.

To calibrate the Clark model, interstage soluble BOD data were collected from 11 RBC facilities that contained from three to six RBC stages where dissolved oxygen and organic overloads were not factors.[1] Relevant data pertaining to each facility are presented in Table 25. The large number of air drive facilities was not considered an adverse factor in calibrating the model, since the use of only organically underloaded facilities minimized any anticipated difference in the performance between air and mechanical drive systems.[2] Table 26 presents the range of influent conditions for the 11 facilities.

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[1] First stage loading was less than 6.4 lbs/day/1,000 sf BOD.

[2] If there exists an advantage to air drive, it would be most apparent in overloaded facilities where systems are oxygen limiting.

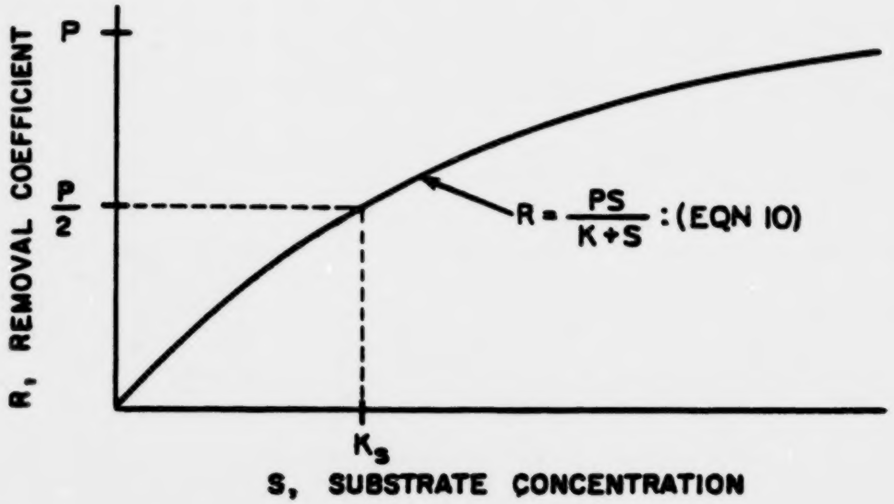

Figure 23. Graphical representation of Equation 10.

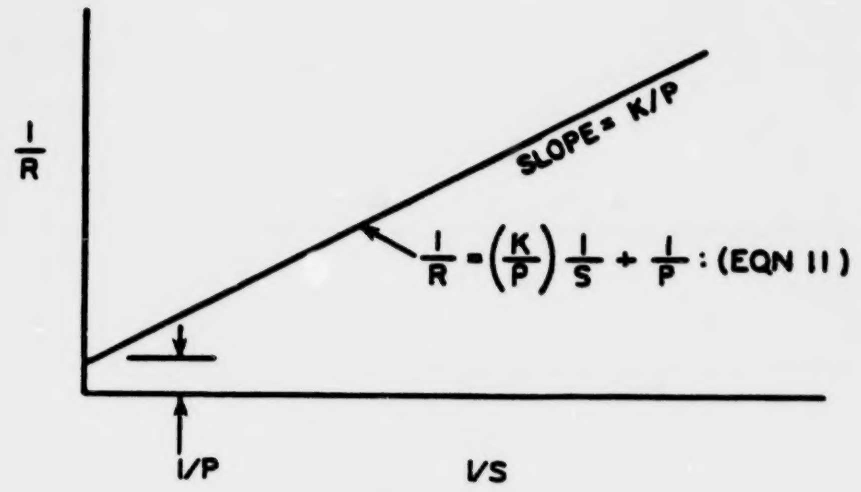

Figure 24. Linearization of Equation 10.

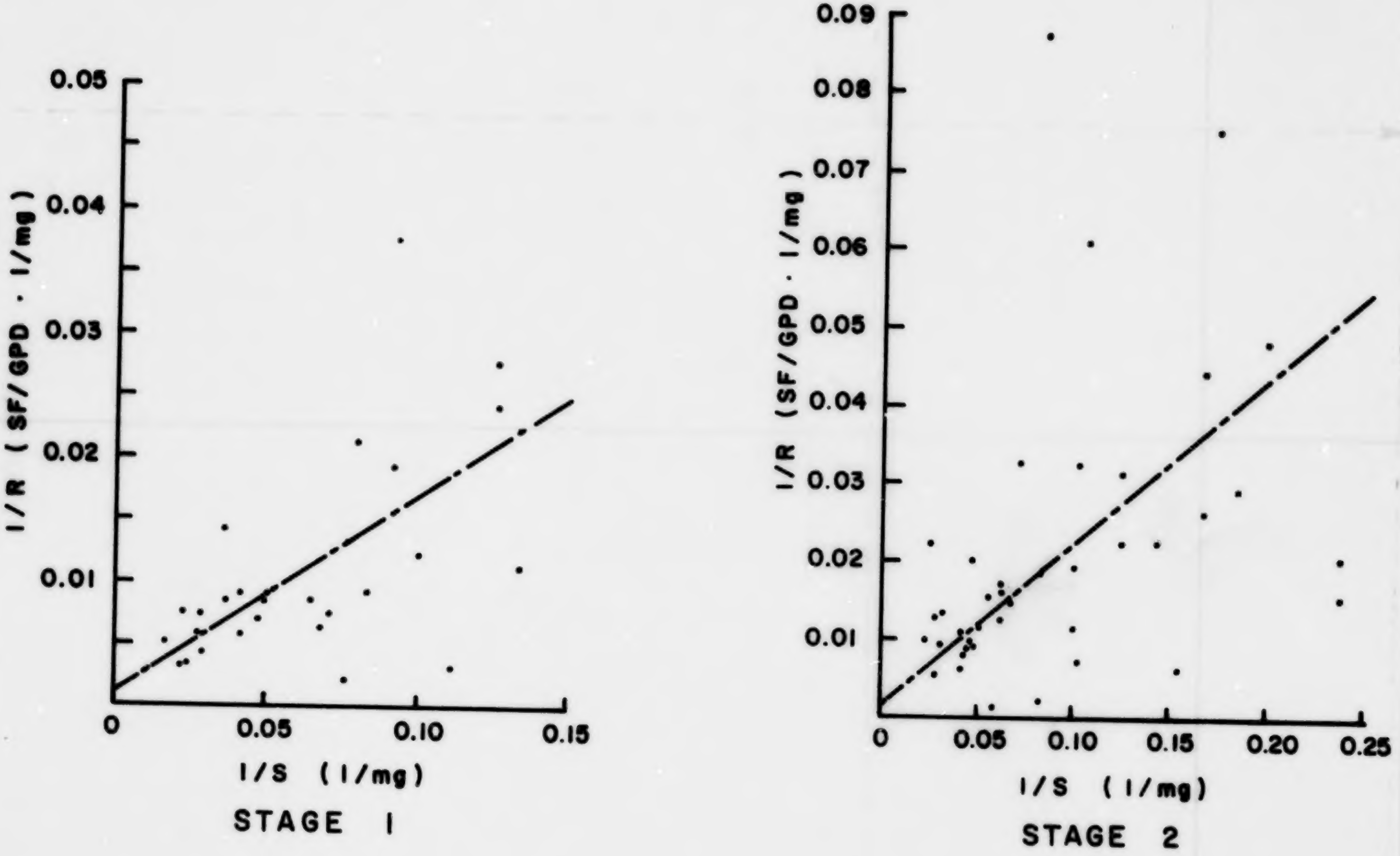

Figure 25. Data analysis, I/R vs. I/S.

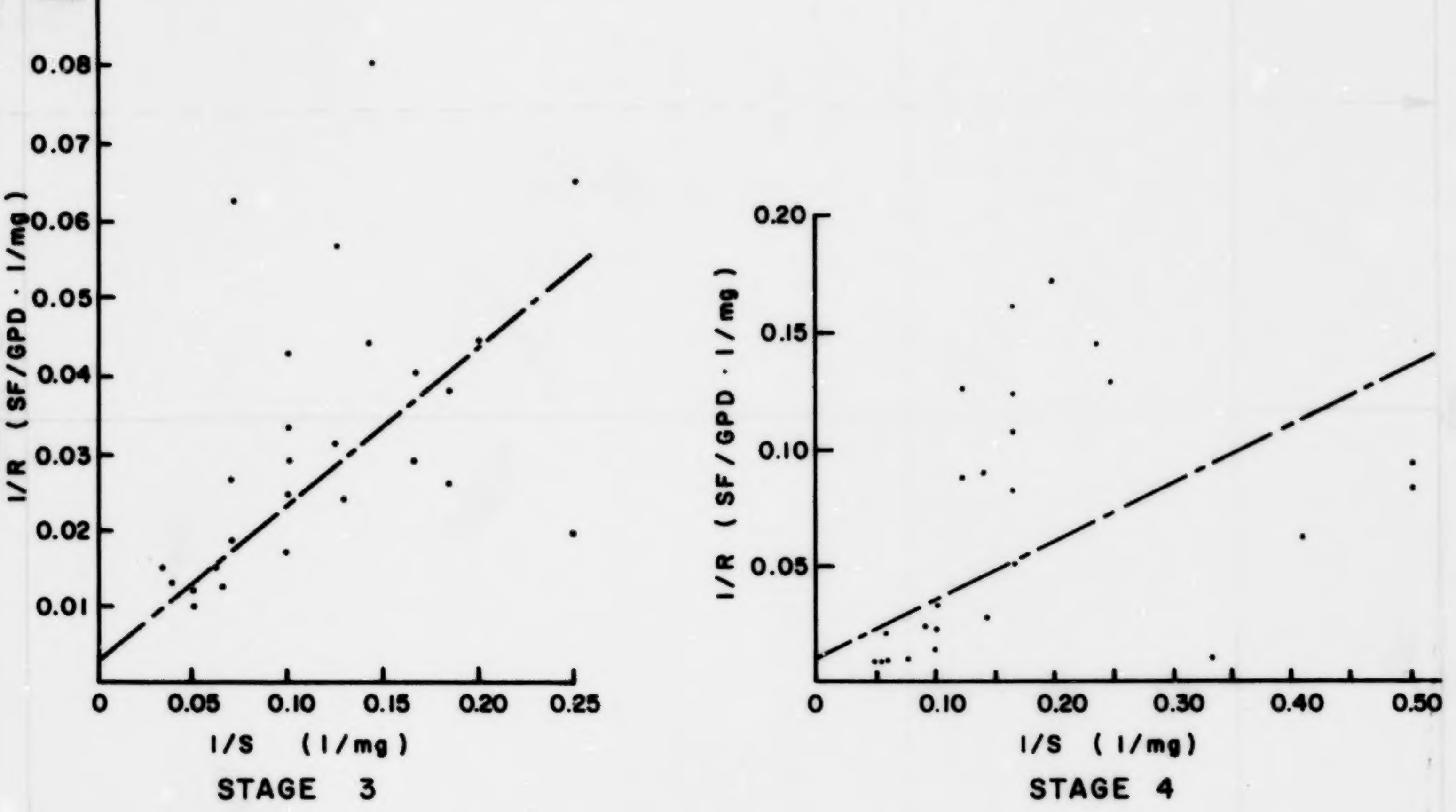

Figure 26. Data analysis, I/R vs. I/S. /S

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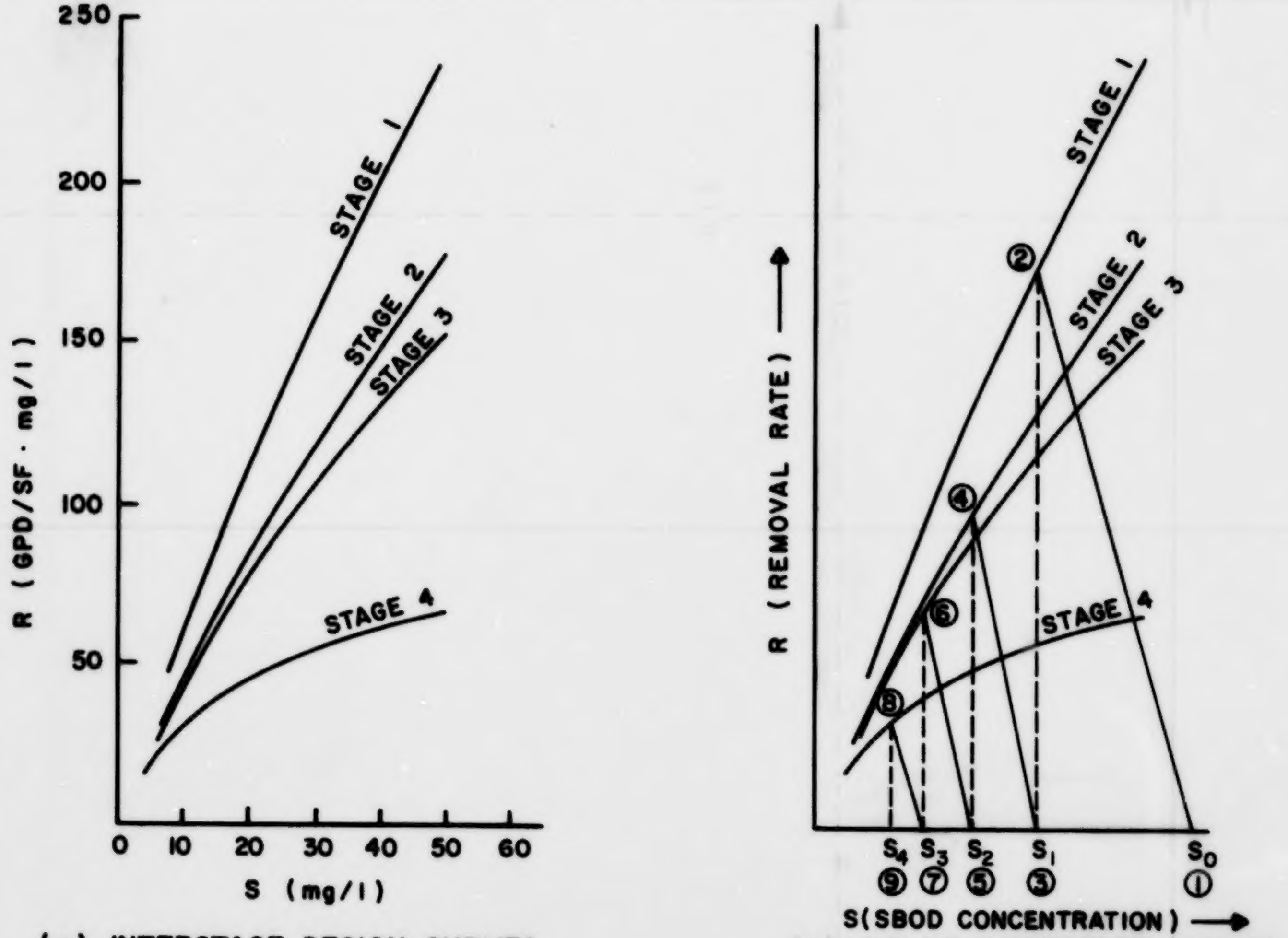

(a) INTERSTAGE DESIGN CURVES

(b) USE OF INTERSTAGE CURVES
(REFER TO PAGE 121 FOR DISCUSSION)

Figure 27. Interstage design curves.

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TABLE 25. DESCRIPTION OF RBC PLANTS USED TO CALIBRATE MODEL

			Average conditions survey period		
Plant	No. of stages	Type of drive	Hydraulic loading gpd/sf	Influent SBOD[1] mg/L	Effluent SBOD mg/L
Milwaukee, WI	4	Mechanical	1.62	69	11
Milwaukee, WI	4	Air	1.69	69	9
Fort Knox, KY	6	Mechanical	1.03	23	2
Cleves, OH	3	Air	0.38	40	3
Enumclaw, WA	4	Air	1.04	168	6
Lancaster, WI	4	Air	0.44	218	8
Woodburn, OH	4	Air	0.75	226	7
Lower East Fork, OH	4	Air	0.99	20	5
Glenwood Springs, CO	4	Air	1.29	43	5
Dodgeville, MI	3	Air	0.56	37	4
West Dundee, MI	3	Air	1.08	101	8
Hartford, MI	4	Air	2.88	17	8
Clark Model Notation	n	---	F/A	S_o	S_i

[1] Influent to RBC units.

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TABLE 26. RANGE AND AVERAGE OPERATING CONDITION FOR 11 FACILITIES USED IN MODEL CALIBRATION

	Range	Average
RBC Influent SBOD, mg/L	10 - 95	55
Hydraulic Loading, gpd/sf	0.4 - 1.5	1.3

Using both the removal coefficient, R, and the soluble BOD concentration in the reactor, S, the model was calibrated as follows. Values of (1/R) vs (1/S) were plotted for each stage of all 11 plants. The area capacity constant, P, and the half-velocity coefficient, K_S, were computed from these graphs. The graphical analysis for the four consecutive stages are presented in Figures 25 and 26, respectively.

The results are presented in Table 27.

TABLE 27. CALIBRATED AREA CAPACITY CONSTANT, P, AND HALF-VELOCITY COEFFICIENTS, K_S (SOLUBLE BOD)

	Maximum removal rate, P		Half-velocity coefficient, K_S
Stage No.	gpd/sf - mg/L	lb/day/1,000 sf	mg/L
1	1,000	8.34	161
2	667	5.56	139
3	400	3.34	82
4	100	0.83	25

The values of P and K were subsequently used to plot an R, removal coefficient, vs S, concentration, curve (Equation 10) for each stage. The four curves generated by this method (one for each stage) are presented in Figure 27(a). Figure 27(b) presents a graphical description of the steps involved in using the curves for design. Referring to Figure 27(b), given a desired effluent concentration, the area required for each stage can be determined as follows:

1. Starting with an influent SBOD concentration, S_o, a line is drawn between this influent SBOD concentration (point 1 on Figure 27(b)) and the point of intersection of the R vs S curve with the desired effluent SBOD concentration, S_i (point 2 on Figure 27(b)). The slope of this straight line on the R vs S plane defines the hydraulic loading. This can be shown as follows:

   per Equation 9, $R = \frac{F(S_o - S_i)}{A}$

2. The slope of this line can be defined by:

$$\text{Slope} = \frac{\Delta R}{\Delta S_o} = \frac{0 - R_i}{S_o - S_i} \qquad (12)$$

3. Substituting Equation 9 into Equation 10 yields:

$$\text{Slope} = \frac{0 - \frac{F}{A}(S_o - S_i)}{(S_o - S_i)} = - \frac{F\ (S_o - S_i)}{A\ (S_o - S_i)} = - \frac{F}{A} \qquad (13)$$

The analysis may be continued for each successive RBC stage (points 3 to 9 on Figure 27(b)). The SBOD concentration in the last reactor, S_4, is the SBOD concentration in the final effluent.

The concentration in a given reactor can be derived directly by setting Equation 9 equal to Equation 10 as follows:

$$R = \frac{F_i}{A_i}(S_o - S_i) = \frac{P_i S_i}{K_i + S_i} \qquad (14)$$

Solving for S_i yields:

$$S_i = \frac{\left[[HL_i(S_o - K_i)] - P_i\right] + \left[[HL_i(S_o - K_i) - P_i]^2 + [4(HL_i)^2](K_i)(S_o)\right]^{1/2}}{2(HL_i)} \qquad (15)$$

where,

i = RBC stage under analysis

S_o = influent SBOD concentration to stage i (mg/L)

HL_i = hydraulic loading for stage i (gpd/sf) = $\frac{F_i}{A_i}$

S_i = effluent SBOD concentration for stage i (mg/L)

P_i = area capacity constant for stage i (gpd/sf-mg/L)

K_i = half-velocity coefficient for stage i (mg/L)

F_i = wastewater flow rate to stage i (gpd)

A_i = surface area in stage i (square feet)

Equation 15 can be used to solve for the SBOD concentration from any stage given the hydraulic loading and influent SBOD concentration when P_i and K_i are known.

To determine the hydraulic loading given the influent SBOD concentration and the required effluent concentration, Equation 12 can be rearranged as follows:

$$HL_i = \frac{(P_i)(S_i)}{(K_i + S_i)(S_o - S_i)} \qquad (16)$$

An example illustrating the use of this model is presented in Appendix E.

Comparison of the Model Prediction with Field Observations

To assess the accuracy of the design model, a comparison between the observed field performance of the 16 RBC facilities surveyed and listed in Table 10 and the calibrated model was undertaken. Since plant data collected from the 16 facilities were BOD and the model was calibrated using SBOD, it was necessary to assume an SBOD:BOD ratio to permit a direct comparison between the model and the field data. The ratio was assumed to be 0.5 for both influent and effluent BOD. The model results were generated using a four-stage RBC system with influent concentrations and hydraulic loadings equivalent to the field data.

The results of the analyses are presented in Figure 28 which compares the model prediction to the results displayed previously in Figures 14 and 15. Model predictions are tabulated in Appendix F.

Figure 28(a) presents the data as organic removal in lbs/day/1,000 sf vs hydraulic loading in gpd/sf, and Figure 28(b) presents the data as organic removal vs organic loading, both in lbs/day/1,000 sf. From Figure 28(a) it can be seen that the model is more accurate (i.e., with respect to the regression line) for the lower ranges of BOD concentration, hydraulic loading, and organic loading.

The lack of correlation at higher concentrations and loadings can be attributed to the relatively low concentration range in which the model was calibrated being transport limiting. Calibrated values of P and K_S do not reflect the increase in substrate transport and, hence, utilization, which occurs with higher concentrations.

Comparison of Model to Vendor Design Curves

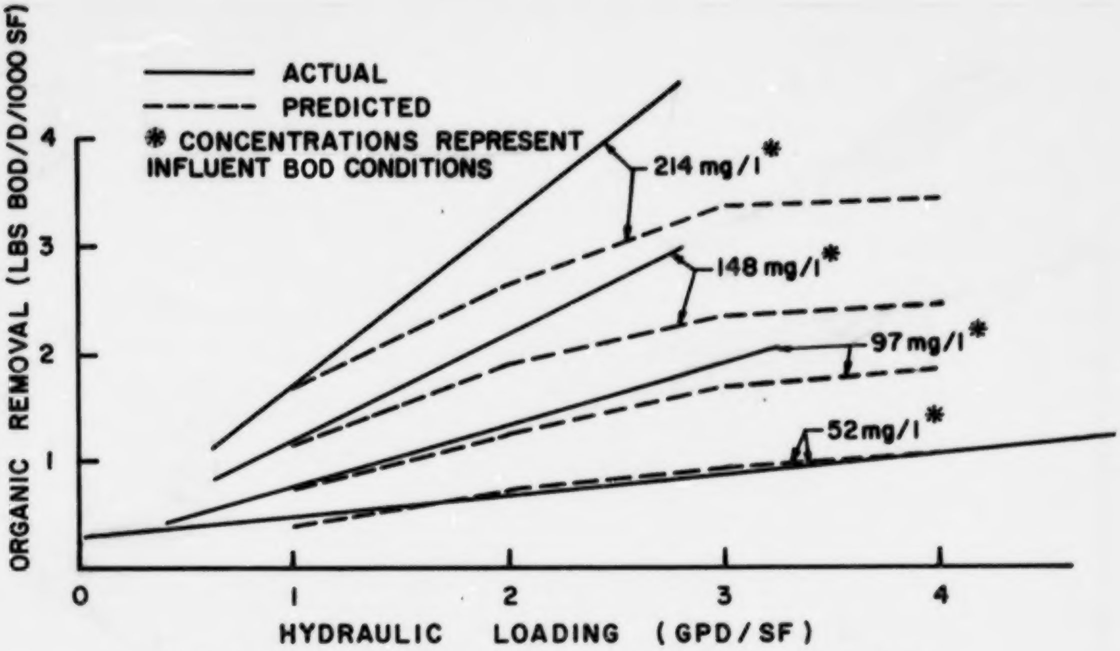
It can be seen by comparing Figure 28 to Figure 18 that the model predictions are more conservative than the manufacturers' curves. The model is always coincident or below the field performance regression line, while manufacturers' data are always coincident or above the field performance regression line.

Recommendations Concerning the Use of the Model

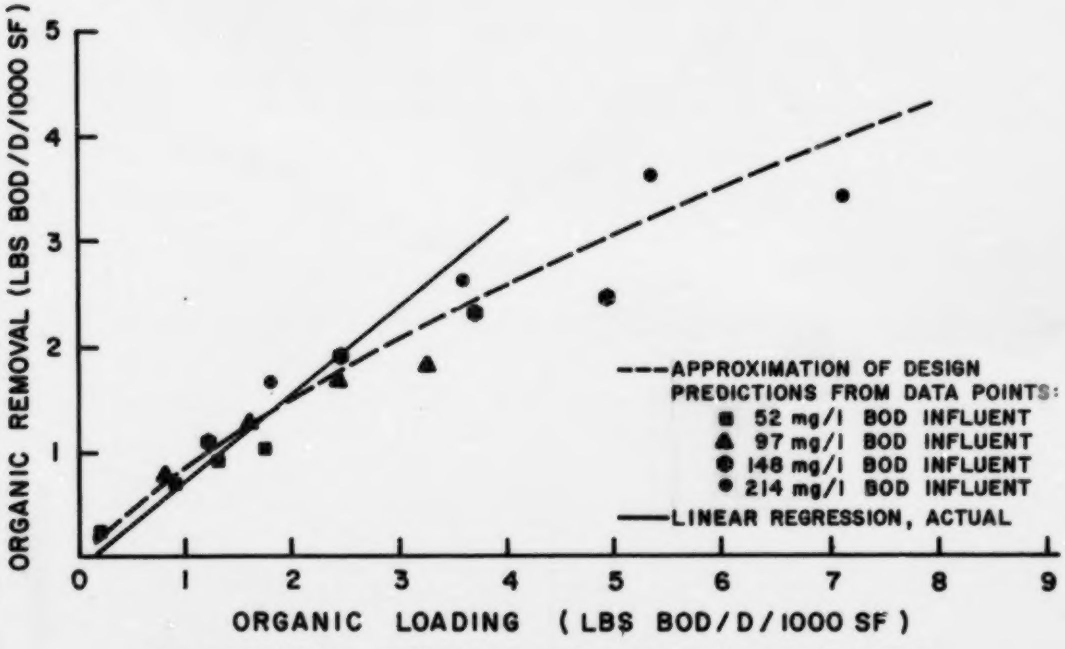
The interstage model presented is a simplified but rational method of projecting RBC performance. The limitations in its use as presented in this report are:

1. Only limited interstage data were available for its calibration.
2. The data available were soluble BOD which requires assumptions concerning SBOD to BOD ratios.
3. It is limited to lower concentration ranges over which it predicted actual performance most accurately (less than 100 mg/L BOD; Figure 28(a).

Such a model is a first step in collecting input data which should be used to test the model over a variety of flows and loadings. For the low influent concentration ranges over which the model was tested the results were better than those predicted by manufacturers' design methods.



(a) ORGANIC REMOVAL VS. HYDRAULIC LOADING



(b) ORGANIC REMOVAL VS. ORGANIC LOADING

Figure 28. Comparison of actual performance to design predictions.

One of the major advantages of this model is that it can predict RBC interstage performance and allows for an assessment of variations in several design features, such as staging, distribution of surface area, and step feeding.

Staging --

Recommendations by manufacturers (2, 49) suggest increasing the number of stages in an RBC system to improve performance (Table 9). The calibrated design model was used to predict the benefits of staging by assessing the amount of surface area required to achieve BOD removal efficiencies of 50 percent, 60 percent, 75 percent, 85 percent, and 95 percent for one, two, three, and four stages with influent conditions of:

Flow = 1 mgd
RBC Influent SBOD = 50 mg/L (BOD = 100 mg/L, assuming SBOD:BOD = 0.5)

Results are tabulated in Appendix G, and are presented in Figure 29. The results presented in Figure 29 illustrate that for high levels of removals, multistage systems require less surface area than single stage systems to achieve a given percentage removal.

Optimum staging conditions can be defined from Figure 29 as follows:

Desired BOD removal efficiency[1] percent	Optimum No. of stages
50	1
60	2
75	3
85	3
95	4

Caution, however, must be used when increasing the number of stages to ensure that an organic overload condition is not created (i.e., the loading per stage does not exceed 6.4 lbs/day/1,000 sf).

Finally, the staging of single shaft RBC systems must account for the loss of surface area required by the insertion of baffles, which is reported to be approximately 12 percent of the total shaft area per stage (2).

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[1] The reported advantages of staging RBC systems with respect to nitrification were addressed in Section 9.

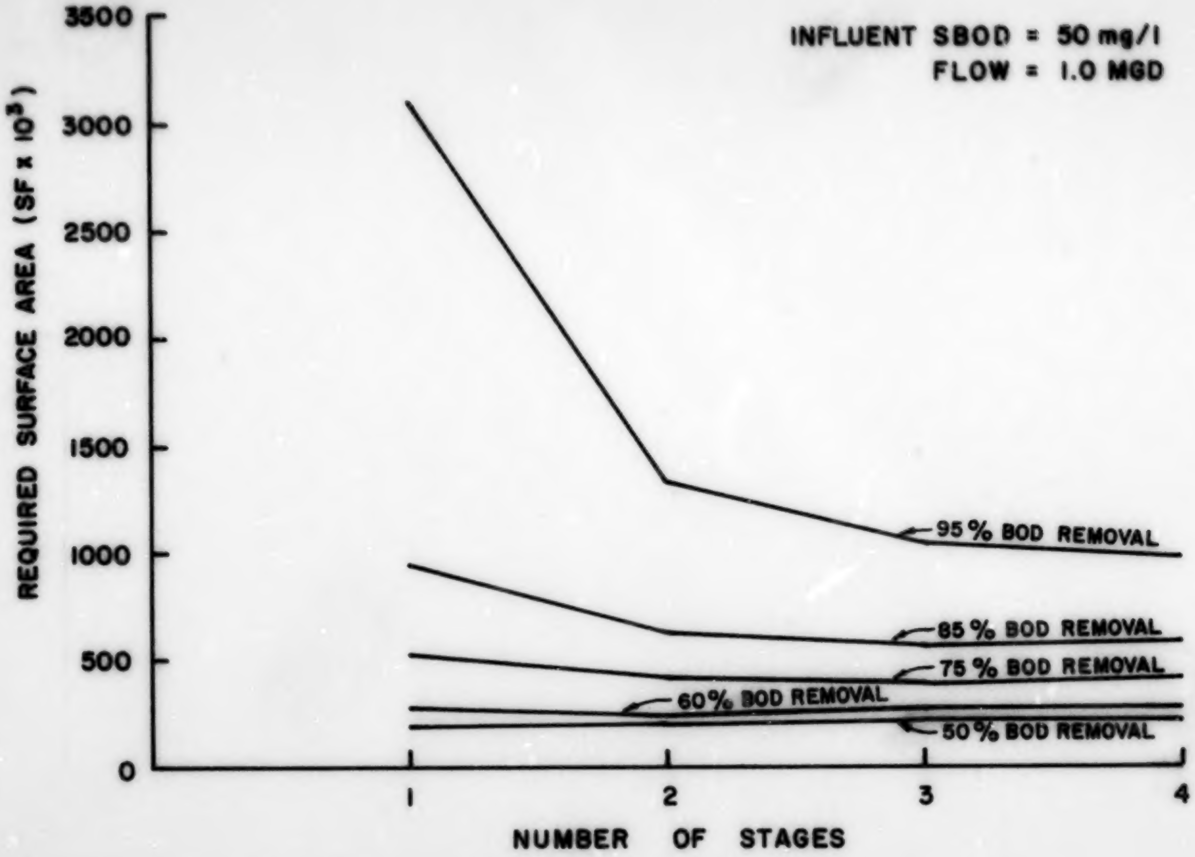

Figure 29. Effect of staging on surface area requirements.

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Area Distribution Effects --

Current design practice distributes area equally among all stages with removable interstage baffles providing the flexibility to combine two or more stages into one. To assess the benefits that altering the percentage of total area per stage might provide, the interstage model was used to predict BOD removal rates for a four-stage, a three-stage, and a two-stage RBC system containing equivalent total areas. Various configurations were assessed over hydraulic loading ranges from 1 to 3 gpd/sf and an influent of 50 mg/L SBOD. The distribution of area and the percent BOD removal predicted by the model for each case is presented in Table 28.

The model results illustrate insignificant changes in percent efficiency with variations in area distribution, provided that overall surface area remains the same. Dissolved oxygen limitations, caused by loading the first stage of the system beyond the 6.4 lbs BOD/day/1,000 sf organic loading limit, remains the single most important factor in sizing the first stage. Subsequent stages must consider the practical aspects of uniform shaft sizes provided by manufacturers in sizing of the remaining stages.

Step Feeding --

Step feeding an RBC system involves the distribution of the influent waste flow in varying proportions to downstream stages to distribute more evenly the influent loads to each RBC stage. None of the operating plants contacted during this survey had step feeding incorporated in their design or have attempted to modify operations to provide such capability.[1]

The model developed cannot be used directly to predict the response of the system to step feeding since values of P and K_s for each stage were developed from systems with sequential stage-wise flow through. Introducing wastewater into the second stage would be expected to alter the kinetics (i.e., P_2 and K_2) by altering the nature of the wastewater entering this stage. This problem can be mathematically addressed in the model by accounting for the relative quantities of influent flow which are diverted to downstream stages, but which exhibit values of P and K_s associated with the initial stages of the system.

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[1] Facilities not included in this survey were identified with step feeding.

TABLE 28. AREA DISTRIBUTION EFFECTS

	Percent of total area				Percent BOD removal		
	Stage No. 1	Stage No. 2	Stage No. 3	Stage No. 4	At hydraulic loading = 1 gpd/sf	At hydraulic loading = 2 gpd/sf	At hydraulic loading = 3 gpd/sf
Four Stage	70	10	10	10	93	80	69
	50	30	10	10	95	82	70
	40	30	20	10	95	82	70
	25	25	25	25	95	81	65
Three Stage	80	10	10	---	92	79	69
	60	20	20	---	94	82	71
	40	30	30	---	95	82	71
	33	33	33	---	95	82	70
Two Stage	90	10	---	---	89	77	67
	70	30	---	---	92	80	69
	60	40	---	---	92	80	70
	50	50	---	---	92	80	69

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The mathematical analysis is presented graphically in Figure 30. An example of this analysis is as follows:

Assume in a four-stage RBC system:

40 percent of the flow enters the first stage, while
30 percent of the flow is diverted to the second stage,
20 percent to the third stage, and
10 percent to the fourth stage.

The following kinetic coefficients would act in each stage and on each segment of flow:

Stage	Relative flow percent	Influent conditions Q	Influent conditions S	Reaction coefficients P	Reaction coefficients K
1	40	Q_1	S_O	P_1	K_1
2	30	Q_2	S_O	P_1	K_1
2	40	Q_1	S_{1-1}	P_2	K_2
3	20	Q_3	S_O	P_1	K_1
3	30	Q_2	S_{2-2}	P_2	K_2
3	40	Q_1	S_{2-1}	P_3	K_3
4	10	Q_4	S_O	P_1	K_1
4	20	Q_3	S_{3-3}	P_2	K_2
4	30	Q_2	S_{3-2}	P_3	K_3
4	40	Q_1	S_{3-1}	P_4	K_4

The results of the model analysis, for an influent SBOD of 50 mg/L and a hydraulic loading of 1 gpd/sf, are tabulated in Table 30 with notations specified in Figure 30. The results given in the final two columns of Table 30 indicate no advantage to step feeding and a potential decrease in performance if too much flow is diverted to downstream stages. For example, no step feed (100 percent flow to Stage 1) yields a 95.2 percent SBOD removal. An 80, 10, 10, 0 percent split to each of the four respective stages yields a 94.1 percent SBOD removal; a 60, 20, 10, and 10 split yields a 92.1 percent SBOD removal. Other flow distributions are presented in Table 29.

The results of this analysis indicate that for organically underloaded conditions there is no advantage to step feeding. If any advantage exists, it would be associated with an attempt to relieve an overloaded condition in the first stage. The model, however, is not able to address overloaded conditions.

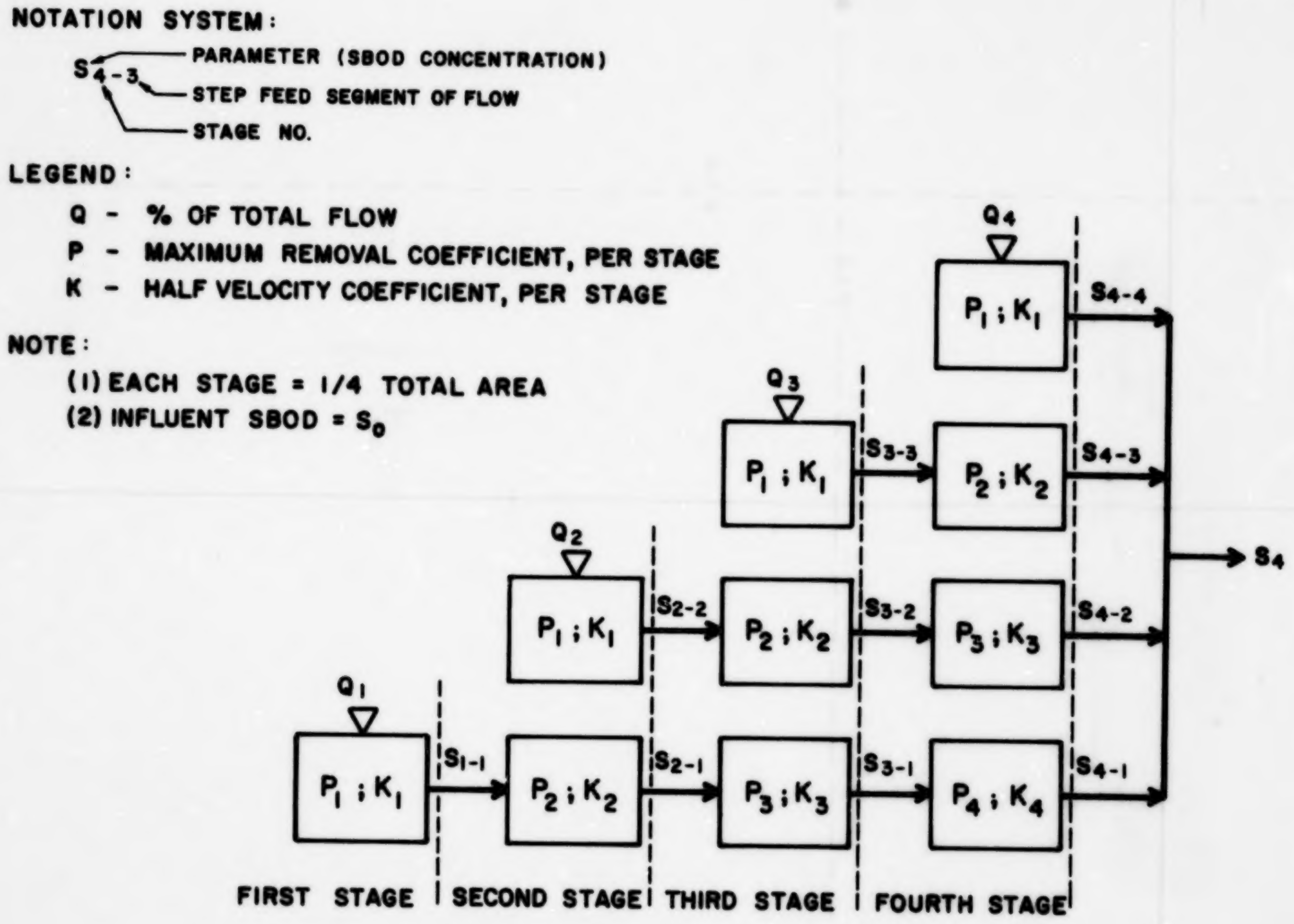
NOTATION SYSTEM:
S_{4-3}
PARAMETER (SBOD CONCENTRATION)
STEP FEED SEGMENT OF FLOW
STAGE NO.
LEGEND:
Q - % OF TOTAL FLOW
P - MAXIMUM REMOVAL COEFFICIENT, PER STAGE
K - HALF VELOCITY COEFFICIENT, PER STAGE
NOTE:
(1) EACH STAGE = 1/4 TOTAL AREA
(2) INFLUENT SBOD = S_0
Q_4
$P_1 ; K_1$
S_{4-4}
Q_3
$P_1 ; K_1$
S_{3-3}
$P_2 ; K_2$
S_{4-3}
Q_2
$P_1 ; K_1$
S_{2-2}
$P_2 ; K_2$
S_{3-2}
$P_3 ; K_3$
S_{4-2}
S_4
Q_1
$P_1 ; K_1$
S_{1-1}
$P_2 ; K_2$
S_{2-1}
$P_3 ; K_3$
S_{3-1}
$P_4 ; K_4$
S_{4-1}
FIRST STAGE
SECOND STAGE
THIRD STAGE
FOURTH STAGE

Figure 30. Step feed analysis.

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TABLE 29. STEP FEED ANALYSIS

Percent of total flow (Q)				Reactor (and effluent SBOD) concentrations per stage (mg/L)				Final effluent BOD concentration (mg/L) (S_4)	Overall percent BOD removal
Stage 1 (Q_1)	Stage 2 (Q_2)	Stage 3 (Q_3)	Stage 4 (Q_4)	Stage 1 (S_{4-1})	Stage 2 (S_{4-2})	Stage 3 (S_{4-3})	Stage 4 (S_{4-4})		
100	0	0	0	2	---	---	---	2	96
80	10	10	0	2	4	10.0	---	3	94
70	10	10	10	2	4	9.	21	4	92
70	30	0	0	2	5	0	---	3	94
60	20	10	10	1	3	8.	21	4	92
60	40	0	0	2	5	0	---	3	94
50	25	12.5	12.5	1.	4	9.1	21	6	88
50	30	10	10	1.	3.	9.	21.	4	92
50	50	0	0	1.	5	---	---	3	94
40	20	20	20	1	3	9	21	7	86
40	30	20	10	1	3	9.	21.	5	90
34	33	33	0	1	4	10.	---	5	90
25	25	25	25	1	2	8.	21	8	84

Influent Conditions:

Overall Hydraulic Loading: 1 gpd/sf
Influent SBOD Concentration: 50 mg/L

Another potential use for step feeding is its ability to distribute the influent flow more equally to a multishaft stage. For example, in a three, four, or five shaft, first stage concern over plug flow through a given reactor and the potential for an overload occurring on the first and/or second shaft of the stage could be alleviated by providing for a more evenly distributed loading. Step feeding can provide this additional flexibility.

DESIGN GUIDANCE

The design of fixed film RBC systems has proven to be more difficult than originally envisioned when RBC's were introduced into this country in the late 60's and early 70's. Continual data collection and evaluation provides input which will continue to improve RBC design and process control flexibility. RBC design today, however, requires a combined application of available design methodologies, a review and comparison of the performance of facilities with similar input conditions and design criteria with the various design methodologies, and provisions for increased operational flexibility. The following suggestions are intended as design guidance:

RBC design normally starts with an effluent quality goal defined either by BOD_5, BOD_5 and NH_3-N, or UOD.[1] To proceed with the RBC design, the following tasks are involved:

1. Identify and quantify all influent loadings.
2. Determine the required surface area.
3. Determine the number of stages and area distribution per stage.
4. Evaluate influent flow distribution.
5. Evaluate the desired number of process trains.
6. Consider added operational flexibility options which include:
    a. Step feed.
    b. Recycle.
    c. Supplemental air.
    d. Rotational velocity - variable speed.
    e. Structural load cells.

---

[1] UOD (ultimate oxygen demand) is normally defined as follows: $UOD = 1.5 (BOD_5) + 4.57 (NH_3\text{-}N)$.

7. Consider pilot plant requirements.

8. Define all potential sidestreams.

Influent Loadings

The identification and quantification of all influent waste sources to the RBC is necessary to accurately quantify first stage BOD loadings and to assess total surface area requirements.[1] It is also necessary to determine the degree of uncertainty associated with influent waste stream characteristics (e.g., BOD and flow) so that increased flexibility or safety can be incorporated into the facility operation or design.

Although not included in the scope of this report, NH_3-N loading must be identified if NH_3-N or UOD is a design effluent condition. Recent concern associated with wastes containing high sulfide concentrations[2] warrant its identification as an influent source.

RBC loads are best subdivided into two types: those loads used to size total surface area requirements and those used to assess first stage loading limitations. This differentiation stems from the fact that organic overloads, particularly in the first stage, were observed to be highly susceptible to slug sidestream loadings, septage loading, and hydraulic peaks, which induce nuisance organism growths which result in reduced RBC performance. In addition, proper first stage loading reduces the chances of shaft failure, which occurs most frequently in the first stage.[3] This process and structural susceptibility warrants some additional care in first stage loading design.

Total Surface Area Design Loadings --

Influent load identification must include sidestream and septage, as well as the raw input loading. Sidestreams normally include gravity thickener recycle, aerobic or anaerobic digester supernatant, and dewatering operation supernatant (e.g., vacuum filter, filter press, drying beds). Raw loadings, sidestreams, and septage BOD loads are normally quantified in terms of daily loads (e.g., lbs/day) equalized over the course of a day. Given this methodology for defining influent loads, the sidestream and septage load will, in most cases, contribute less than 5 percent of the total influent load.[1] However, if insufficient equalization is provided in the design to spread these loads, then they have to be considered in the design. Sizing for total surface area using the equalized raw load and sidestream load was judged to be acceptable practice, provided hydraulic peaks are not excessive.[2]

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[1] RBC influent loads are primary effluent loads.

[2] See Section 4 for more detailed discussion.

[3] See Section 8 for more detailed discussion.

First Stage Surface Area Design Loadings --

First stage loading design calculations, however, warrant more precise considerations which include the intermittent nature of the loadings, potential variations in process train flow distribution, complete mixing in the reactor, and hydraulic peaking.

Intermittent loadings -- Intermittent sidestreams will exert a greater loading (i.e., rate of application) to the RBC than one which is continuous over the course of the day.

Flow distribution variations -- Multiprocess train RBC systems must be designed hydraulically to split the flow evenly to all process trains.

Complete mixing -- Any loading calculation assumes a completely mixed reactor. In multishaft stages, true complete mixing is less likely to occur than in single shaft stages. The result is that in multishaft reactors, the first shaft is more likely to receive a higher load than downstream shafts and sequencing batch reactors is approached.

Hydraulic peaking -- First-stage loading should account for average peak hourly flows which could be approximately 1.5 times the average daily flow (81). This will provide sufficient safety for normal diurnal variations.

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[1] Load to the primary clarifier, since sidestreams are normally returned to the influent of the primary clarifier.

[2] A 2.0 to 2.5 peaking factor has been suggested as a limiting peak; see Section 4 for more detailed discussion.

First stage design then requires the calculation of:

1. Raw wastewater loading in total lbs per day.

2. Intermittent wastewater loadings, defined by the total lbs divided by the portion of the day over which it is applied.

3. A correction of 1.2 times the above loading to account for average hourly hydraulic peaking.

4. An additional loading adjustment of 1.1 times the average hourly hydraulic peak loading to account for flow variations between process trains in multiprocess train systems (which can vary by as much as 10 percent even in good hydraulic designs).

5. An additional loading adjustment of at least 1.1 to account for errors in assuming complete mixing in reactors with three or more shafts. (Based on observations in multishaft facilities, errors in assuming complete mixing can occur in reactors with three or more shafts. A 10 percent error is judged to be reasonable for a three-shaft stage.)

The following example, with a raw wastewater loading of 1,168 lbs/day of BOD, illustrates the above guidelines:

1. An intermittent sidestream load of 50 lbs applied over a four-hour period, or a rate of 300 lbs/day, results in an overall loading of 1,468 lbs/day.

2. Average hourly hydraulic peak adjustment of 1.2 results in a total load of 1,762 lbs/day.

3. A flow distribution adjustment of 1.1 for a multiprocess train system results in an adjusted load of 1,938 lbs/day.

4. Finally, an adjustment of 1.1 for complete mixing errors in a three-shaft stage results in a final loading of 2,132 lbs/day, to be used in the design of the first stage.

Required Surface Area

Methods currently available to define the required total surface area include the use of vendor design curves, published data defining performance as a function of hydraulic or organic loading, as presented in Section 8, or models such as the one developed in this section. Each method has its limitations.

Manufacturers' design curves do not fit observed field data in all ranges of influent flow and loading. Observed field data are highly dependent on the site-specific experience at given installations, which may or may not be RBC related (unaccounted for sidestream loadings, poor secondary clarifier design or performance could affect RBC performance). The model presented in this report is limited in effectiveness to the low-influent BOD concentrations and organic loadings previously defined.

Manufacturers' design curves are used almost exclusively in the field today to define total RBC surface area. It is anticipated that they will continue to be used for design guidance until more rational approaches are demonstrated. It is recommended, however, that process design include a design analysis performed by an examination of published field data, vendor design data, and available models to apply the current state-of-the-art to design. Field visits to RBC facilities which are similar (wastewater characteristics and design) to the projected requirements of the facility under investigation are recommended.

Number of Stages and the Area Distribution Per Stage

The staging model analysis presented in this section indicates that staging is desirable to achieve low-effluent concentrations. The results are similar to those projected by vendors. Staging is also desirable for systems with nitrification to provide for better process control and to isolate stages so that the development of nitrifying biota can be promoted.

In systems that are not organically overloaded, no particular advantage is associated with variations in the amount of area per stage. The only consideration relative to area distribution is that associated with organic overloads in the first stage. This is one of the major design concerns in an RBC system. RBC's should be loaded below the 6.4 lbs/day/1,000 sf per stage BOD limitation presented. This normally applies to the first stage of the RBC system. The first-stage loading should be assessed using loading calculation techniques similar to those previously presented.

Influent Load Distribution

Consideration should be given to the influent load distribution, particularly in the first stage, to assist in providing completely mixed reactors. This includes the use of perpendicular, rather than parallel, flow and provisions for adequate reactor mixing wherever possible.[1]

Number of Process Trains

Multi-RBC process trains increase flexibility in operation and design. Initial flow rates to most facilities are considerably less than anticipated design flow rates. With multiprocess trains, all the process trains need not be in operation when flow is less than design. In systems with only one process train, even if the flow rate is less than design, operation of all the shafts is required.

Increasing the number of process trains also reduces the first-stage loading per train. By increasing the number of process trains, it should be possible to reduce the total required first-stage area and the number of shafts in the first stage. As previously mentioned, complete mixing and evenly distributed loadings are less likely in multishaft stages.

Additional Flexibility

One of the advantages of an RBC system is the relative simplicity of operation. The operator of an RBC system need only keep the media rotating and need not be concerned with strict process control requirements such as those associated with activated sludge systems. This advantage, however, is also characterized by a lack of operating flexibility. The operator can do very little to improve performance if process problems develop. Some of the recommendations presented below are intended to help increase process and operating flexibility.

Step Feeding

No apparent advantage exists for step feeding properly designed RBC systems in which overloaded conditions will not occur. Provisions for step feeding in multishaft stages, however, can provide a means to more evenly distribute the loading to each shaft. In multistage systems, step feeding provides additional flexibility, if overloading does occur, to distribute loadings to downstream stages.

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[1] See Section 4 for more detailed discussion.

Recycle

Some of the reported advantages to recycling effluent include additional alkalinity to reduce chemical costs associated with nitrification, pH maintenance, a denitrification carbon source, and an additional oxygen source available in the recycled nitrate. Recycling, however, also increases the hydraulic and organic loading to the system.[1] No great advantage in recycling to provide increased flexibility was identified in this study and further study is needed to assess its benefits.

Supplemental Air

Supplemental air can be added to RBC systems in the form of air drive utilized to rotate the media or, in addition to mechanical drive, to provide increased operational flexibility. The advantages of supplemental air rests in its reported ability to shear the biomass, maintaining thinner biofilm, which facilitates oxygen penetration to the inner biofilm eliminating or reducing the anaerobic layer.[1] Thinner biomass in air-drive systems has been observed on the surface of the media; however, it is questionable whether the diffused air can penetrate into the internals of the media and effectively shear the film. Thinner biomass also reduces the total weight on the shaft, reducing the probability of shaft failure. In addition, supplemental air creates a buoyant force which helps to lower the total shaft weight load. Potential problems with high sulfide wastes which have been reported, could be partially alleviated with the additional oxygen supply to assist in sulfide oxidation. Finally, RBC systems with supplemental air could allow for a reduction in rotational velocity and associated energy costs; however, the use of supplemental air to reduce energy costs must be assessed in light of the increased capital investment and operating costs associated with the supplemental air.[2]

The scope of this study did not include a detailed comparison between air drive and mechanical drive systems;[3] however, surveys of air drive facilities have yielded information indicating reduced mechanical equipment maintenance requirements resulting from the use of individual compressors to drive several shafts, off-set by additional operating requirements associated with maintaining consistent rotational velocities and air cup replacement. Supplementary information relative to equipment and operational problems in air drive systems is needed.

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[1] See Section 4 for more detailed discussion.

[2] Most air drive RBC systems rotate at 1.2 rpm, while mechanical drive RBC systems rotate at 1.6 rpm.

[3] See Sections 5 and 6 for more detailed discussion.

Rotational Velocity - Variable Speed

The major advantage of variable speed motors is the flexibility to reduce rotational velocity with associated energy savings. Increasing rotational velocity can be utilized as a tool to enhance treatment; however, the exponentially increasing power requirement with increasing rotational velocity is costly. In addition, the effect of the added stress on the shaft and the media at higher rotational velocities is unknown. Variable speed motors should be evaluated in light of their ability to conserve energy (reduce speed) in light of the additional initial investment.

Structural Load Cells

In light of the previous shaft failure history of RBC's, the addition of load cells to monitor weight loading on the shaft is recommended.[1]

Pilot Plant Requirements

Many of the uncertainties in RBC design can be alleviated by piloting, which can establish definitive design parameters. For most RBC system designs, however, the luxury of piloting will not be available. If a pilot plant is available, it is recommended that the full-scale disc diameter size be used in the pilot plant, if possible, to avoid previously reported scale-up problems experienced in RBC pilot plants.[2]

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[1] See Sections 5 and 8 for more detailed discussion.

[2] See Section 4 for more detailed discussion.

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APPENDIX A

INSTALLATION LIST - MUNICIPAL RBC PLANTS

(A) Manufacturer: Autotrol

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
Pewaukee, WI	0.50	EPA Demonstration Grant - Secondary Treatment	8	1971
Edgewater, NJ	0.50	Demonstration of Primary Plant Upgrading	4	1973
Gladstone, MI	1.00	Secondary Treatment and Nitrification	6	1974
Levitt-Selden; Selden, NY	1.30	Secondary Treatment	12	1974
Leisuretown; Lakewood, NJ	0.50	Secondary Treatment	4	1974
Niagara, WI	0.39	Secondary Treatment	2	1974
Carolina Shores; Calabash, NC	0.20	Secondary Treatment	4	1974
Gananda Development; Walworth, NY	0.90	Secondary Treatment	10	1974
Chews Landing; Gloucester, NJ	0.50	Secondary Treatment	4	1974
Battle Ground, WA	0.65	Secondary Treatment	2	1975
Woodland, WA	0.56	Secondary Treatment	2	1975
Ainsworth, NE	0.25	Secondary Treatment	1	1975
Hinckley, IL	0.20	Secondary Treatment and Nitrification	3	1975
North Huntington, PA	1.70	Secondary Treatment	4	1975
Hopkinton, IA	0.20	Combined Dairy and Domestic Waste	4	1975
Richmond, IL	0.40	Secondary Treatment	2	1975
Georgetown, KY	3.00	Secondary Treatment	8	1975
Southhampton Hospital; Southhampton, NY	0.10	Secondary Treatment and Nitrification	2	1975
GAC Utilities; Sarasota, FL	3.00	Nitrification of Activated Sludge Effluent	14	1975

APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued)

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
Boynton Beach, FL	1.40	Upgrading Trickling Filter Effluent	2	1975
Sellersburg, IN	0.20	Secondary Treatment	1	1975
Cadillac, MI	2.00	Nitrification of Activated Sludge Effluent	8	1975
Fulton, IL	0.50	Secondary Treatment	3	1975
Bowling Green, MI	0.30	Secondary Treatment	1	1976
Cresaptown, MD	0.35	Secondary Treatment	1	1976
Buffalo Creek, WV	0.75	Secondary Treatment	5	1976
Hinckley; Medina County, OH	2.00	Nitrification of Activated Sludge Effluent	12	1976
Mobridge, SD	0.50	Secondary Treatment	2	1976
Benton, AR	1.50	Secondary Treatment	4	1976
Newell, WV	0.40	Secondary Treatment	2	1976
Planned Community; Hendricks, IN	0.20	Secondary Treatment	2	1976
Willow Springs County Club; Morrison, CO	0.05	Secondary Treatment	1	1976
Crystal Lake, IL	0.50	Secondary Treatment and Nitrification	4	1976
Clarks Hill, IN	0.15	Secondary Treatment	2	1976
Kirksville, MO	5.00	Secondary Treatment	20	1976
Emmetsburg, IA	0.72	Secondary Treatment	8	1976
York, NE	3.00	Secondary Treatment	16	1976
K.I. Sawyer AFB; Marquetts, MI	1.00	Secondary Treatment	8	1976

APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued)

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
New Martinsville, WV	1.70	Secondary Treatment	5	1976
Murray, NE	0.07	Secondary Treatment	1	1976
Kentucky State Horse Park; Lexington, KY	0.09	Secondary Treatment	2	1976
Lake Lakengren; Preble County, OH	0.15	Secondary Treatment	2	1976
Shenandoah Subdivision; Troy, OH	0.10	Nitrification of Activated Sludge Effluent	1	1976
Aviston, IL	0.12	Nitrification of Activated Sludge Effluent	2	1977
Winchester, KY	1.00	Secondary Treatment	4	1977
Alexandria, VA	54.00	Secondary Treatment	56	1977
Alexandria, VA		Sludge Treatment Supernatant	2	1977
Spencer, IA	3.80	Secondary Treatment and Nitrification	40	1977
Ft. Fairfield, ME	1.30	Combined Potato and Domestic Wastes	5	1977
Chesaning, MI	0.58	Secondary Treatment	3	1977
Monroe, WA	1.40	Secondary Treatment	4	1977
Columbus, IN	12.40	Secondary Treatment and Nitrification	80	1977
Rhinelander, WE	1.90	Secondary Treatment	10	1977
LeSourdsville; Butler County, OH	4.00	Secondary Treatment and Nitrification	20	1977
Crane, IN	1.20	Secondary Treatment	10	1977
Government Camp, OR	0.90	Secondary Treatment	2	1977
Huntley, IL	0.28	Nitrification of Trickling Filter Effluent	4	1977
Brookville, IN	0.60	Secondary Treatment	3	1977

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APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued)

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
Union, OR	0.36	Secondary Treatment	2	1977
Pinecrest, CA	0.218	Secondary Treatment	1	1977
Ft. Knox, KY	6.00	Secondary Treatment and Nitrification	36	1977
Cincinnati MSD; Cleves, OH	1.77	Secondary Treatment and Nitrification	6	1977
Kerens, TX	0.20	Secondary Treatment	1	1977
Gibbon, NE	1.14	Combined Industrial and Domestic Waste	16	1977
Midlothian, TX	0.90	Secondary Treatment	4	1977
Pacesetter Park; Pomona, NY	0.02	Secondary Treatment	1	1977
Watkins, MN	0.18	Combined Dairy and Domestic Waste	2	1977
Northeast Plant; Philadelphia, PA	20.00	Upgrading Activated Sludge Plant	22	1977
Monett, MO	1.53	Combined Industrial and Domestic Waste	20	1978
Yutan, NE	0.12	Secondary Treatment	1	1978
Potomac Heights, MD	0.20	Secondary Treatment	1	1978
Bluefield, WV	3.50	Secondary Treatment	24	1978
Longmont, CO	8.20	Upgrading Trickling Filter Effluent	12	1978
Old Town, ME	1.70	Secondary Treatment	10	1978
Wilton, ME	0.45	Secondary Treatment	4	1978
Toppenish, WA	1.35	Secondary Treatment	6	1978
Mt. Horeb, WI	0.66	Combined Dairy and Domestic; Secondary and Nitrification	8	1978

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APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued)

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
South Point, OH	1.20	Secondary Treatment	3	1978
Washington, PA	6.20	Secondary Treatment and Nitrification	42	1978
Stamping Ground, KY	0.10	Secondary Treatment	1	1978
Perry Park, CO	0.10	Secondary Treatment	1	1978
Three Lakes, WI	0.13	Upgrading Trickling Filter Effluent	1	1978
Hartford, MI	0.35	Secondary Treatment	2	1978
Newman Grove, NE	0.13	Combined Cheese and Domestic Waste	6	1978
Marion, AL	0.50	Secondary Treatment and Nitrification	4	1978
Blue Mounds, WI	0.07	Secondary Treatment	1	1978
Thermopolis, WY	0.60	Secondary Treatment	2	1978
Pueblo Airport; Pueblo, CO	0.30	Secondary Treatment	1	1978
Woodbury, GA	0.32	Secondary Treatment	1	1978
Arapaho Ski Area, CO	0.30	Secondary Treatment	2	1978
Birdsboro, PA	1.00	Upgrading and Nitrification of Trickling Filter Effluent	8	1979
Waymart, PA	0.21	Secondary Treatment and Nitrification	2	1979
Oak Harbor, WA	0.85	Secondary Treatment	4	1979
Ashley, OH	0.19	Secondary Treatment	2	1979
Cheboygan, MI	2.00	Secondary Treatment	8	1979
Bristol, PA	2.70	Secondary Treatment	6	1979

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APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued)

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
St. Clair County; Algonac, MI	2.10	Secondary Treatment	12	1979
Bedford, IN	3.00	Secondary Treatment	12	1979
Superior, NE	0.67	Upgrading Trickling Filter Effluent	3	1979
Ida Grove, IA	0.39	Secondary Treatment	4	1979
Plumborough, PA	1.50	Secondary Treatment and Nitrification	12	1979
Sheldon, IA	0.87	Secondary Treatment and Nitrification	8	1979
Elk River, MN	1.04	Secondary Treatment	4	1979
Myerstown, PA	1.40	Secondary Treatment and Nitrification	8	1979
Lower East Fork; Clermont County, OH	7.00	Secondary Treatment and Nitrification	26	1979
Cranberry, PA	3.00	Secondary Treatment	20	1979
Eagle Grove, IA	0.60	Secondary Treatment and Nitrification	6	1979
Pawnee City, NE	0.13	Secondary Treatment	1	1979
Princeton, IL	1.63	Secondary Treatment and Nitrification	10	1979
Lead-Deadwood, SD	1.15	Nitrification of Activated Sludge Effluent	4	1979
Valley, NE	0.52	Secondary Treatment	3	1979
Dexter, MI	0.70	Secondary Treatment and Nitrification	6	1979
Wapato, WA	1.10	Secondary Treatment	4	1979
New Wilmington, PA	0.57	Secondary Treatment and Nitrification	3	1979
Monticello, WI	0.18	Secondary Treatment	2	1979
Ellsworth, WI	0.66	Secondary Treatment	4	1979

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APPENDIX A
(continued)

(A) Manutacturer: Autotrol (continued)

Plant	Design flow mgd	Treatment	No. of shafts	Date ot start-up
Trancas Canyon; Malibu, CA	0.07	Secondary Treatment	1	1979
Holmes Creek; Cape May, NJ	0.10	Secondary Treatment and Nitrification	1	1979
Winlock, WA	0.18	Secondary Treatment and Nitrification	2	1979
Nelson, PA	0.06	Secondary Treatment and Nitrification	1	1979
East Liberty, OH	0.20	Secondary Treatment	1	1979
Peoria, IL	37.00	Nitrification of Activated Sludge	84	1979
Minneapolis Metro	3.00	Thermal Sludge Conditioning Supernatant	50	1979
Hamilton Township; Trenton, NJ	10.00	Secondary Treatment	48	1979
Manistique, MI	1.50	Secondary Treatment	12	1979
Canonsburg, PA	5.60	Secondary Treatment and Nitrification	40	1979
Easton, PA	10.00	Secondary Treatment	36	1979
Fox Lake, IL	6.00	Secondary Treatment and Nitrification	24	1979
Guelph, Ontario	12.00	Nitrification of Activated Sludge	32	1979
Hampshire, IL	0.48	Secondary Treatment and Nitrification	4	1979
Carrollton, OH	0.55	Secondary Treatment and Nitrification	4	1979
Hickory, NC	6.00	Secondary Treatment and Nitrification	48	1979
Fox River Grove, IL	1.25	Secondary Treatment	4	1979
Crawfordsville, IN	3.40	Secondary Treatment	4	1979
Glenwood Springs, CO	2.31	Secondary Treatment and Nitrification	8	1979

APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued)

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
Smithtown, NY	0.12	Secondary Treatment	1	1979
Fennimore, WI	0.92	Secondary Treatment and Nitrification	8	1979
Winchester, KY	3.00	Addition to Bio-Surf Plant to Upgrade Nitrification	20	1979
Mt. Sterling, KY	3.00	Secondary Treatment and Nitrification	35	1979
Mayville, NY	0.50	Secondary Treatment	3	1979
Lloyd, NY	1.25	Secondary Treatment	6	1979
Honeoye Lake, NY	0.52	Secondary Treatment	2	1979
Pierre, SD	1.58	Secondary Treatment	16	1979
Marion, WI	0.24	Secondary Treatment and Nitrification	3	1979
North Bergen, NJ	10.00	Secondary Treatment	32	1979
Snowmass, CO	1.60	Nitrification of Activated Sludge Effluent	8	1979
Robertsdale, AL	0.38	Secondary Treatment	4	1979
Sabetha, KS	0.50	Upgrading Trickling Filter Effluent	1	1979
MOT STP; Odessa, DE	1.00	Secondary Treatment	5	1980
Fishcreek, Summit County; Stow, OH	3.00	Secondary Treatment and Nitrification	32	1980
Delhi Township, MI	2.00	Secondary Treatment	8	1980
Clinton, MI	0.45	Secondary Treatment	4	1980
Oakridge, NY	0.10	Secondary Treatment and Nitrification	2	1980
Benicia, CA	3.00	Secondary Treatment	12	1980
Fort Bragg, NC	8.00	Upgrading Trickling Filter Effluent	16	1980

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APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued)

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
Brookings, SD	3.00	Secondary Treatment	8	1980
Lancaster, WI	0.74	Secondary Treatment and Nitrification	8	1980
Charlotte, MI	1.20	Secondary Treatment and Nitrification	12	1980
South Clinton County, MI	5.00	Secondary Treatment and Nitrification	42	1980
Marquette, MI	6.20	Secondary Treatment and Nitrification	24	1980
St. Johns, MI	2.50	Secondary Treatment and Nitrification	15	1980
Cynthiana, KY	1.50	Secondary Treatment and Nitrification	12	1980
Eau Claire, WI	16.30	Secondary Treatment	56	1980
Union Sanitary District, CA	20.00	Secondary Treatment	80	1980
St. Louis, MI	0.88	Secondary Treatment and Nitrification	8	1980
Winston-Green, OR	1.60	Secondary Treatment	6	1980
McCook, NE	0.30	Secondary Treatment	15	1980
Woodburn, OR	3.10	Secondary Treatment and Nitrification	16	1980
Upper Tuscarawas Sumit County; Springfield, OH	2.00	Secondary Treatment	12	1980
Canandaigua, NY	7.30	Secondary Treatment and Nitrification	32	1980
Romeo, MI	1.60	Secondary Treatment and Nitrification	15	1980
Random Lake, WI	1.25	Secondary Treatment	8	1980
Sac City, IA	0.48	Secondary Treatment and Nitrification	6	1980
Negaunee, MI	1.60	Secondary Treatment	8	1980
Grosse Ile, MI	2.25	Secondary Treatment	10	1980

APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued)

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
Sanilace County; Croswell, MI	0.50	Secondary Treatment and Nitrification	4	1980
Kwjalein Island	0.45	Secondary Treatment	4	1980
Enumclaw, WA	2.40	Secondary Treatment	121	1980
New Baltimore, MI	1.75	Secondary Treatment	4	1980
Jonesville, MI	0.32	Secondary Treatment	4	1980
Farmington, NM	5.80	Secondary Treatment	8	1981
West Dundee, IL	1.41	Secondary Treatment	3	1981
Orlando, FL	24.00	Secondary Treatment and Nitrification	213	1981
Grand Strand, SC	7.50	Secondary Treatment	20	1981
Plainwell, MI	1.30	Secondary Treatment	6	1981
Hermiston, OR	3.27	Secondary Treatment	8	1981
Lebanon, IN	1.88	Secondary Treatment	10	1981
Tillamook, WA	2.00	Secondary Treatment	4	1981
Blaine, WA	0.80	Secondary Treatment	6	1981
Tallahassee, FL	2.50	Secondary Treatment	3	1981
Cape May, NJ	6.30	Secondary Treatment	20	1981
South Bay, FL	1.40	Secondary Treatment	4	1981

APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued) - Package Plants

Plant	Design flow mgd	Treatment	Date of start-up
U.S. Forest Service, Camp Horseshoe; Tucker County, WV	0.009	Secondary Treatment	1971
Southeast Wastewater Treatment; Brewster, NY	0.030	Secondary Treatment	1971
Boldt Castle, Thousand Islands; Alexandria Bay, NY	0.020	Secondary Treatment	1972
Chelsea Ridge; Rhinebeck, NY	0.030	Secondary Treatment	1972
Cables & Wilson; Hyde Park, NY	0.030	Secondary Treatment	1972
Levitt-Stratmore; Yaphank, NY	0.050	Secondary Treatment	1973
Wingdale Village; Wingdale, NY	0.030	Secondary Treatment	1974
Teen Challenge; Rehrersberg, PA	0.018	Secondary Treatment	1974
Texaco Research; Beacon, NY	0.020	Secondary Treatment	1974
Vernon Township; Vernon, NJ	0.030	Secondary Treatment	1974
Coventry Manor; Coram, NY	0.050	Secondary Treatment	1975
Glacier View Ranch; Ward, CO	0.140	Secondary Treatment	1975
Storage Technology; Louisville, CO	0.010	Secondary Treatment	1975
Grand Portage, MN	0.050	Secondary Treatment	1975
Ramada Inn; Armonk, NY	0.020	Secondary Treatment	1975
Albert Lea, MN	0.005	Secondary Treatment	1975
Swansea Mall; Swansea, MA	0.050	Secondary Treatment	1975
Camp Manitoumi; Lowpoint, IL	0.013	Secondary Treatment	1976
Camp McCain; Jackson, MS	0.005	Secondary Treatment	1976
Abex Corporation; Marysville, OH	0.030	Secondary Treatment	1976

APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued) - Package Plants

Plant	Design flow mgd	Treatment	Date of start-up
Zerbe Sisters Nursing Center; Narvon, PA	0.012	Secondary Treatment	1976
Kyle State Park; Panola County, MS	0.010	Secondary Treatment	1976
Arrowhead North; Mt. Pocono, PA	0.050	Secondary Treatment	1976
Heritage Village; Gillette, WY	0.040	Secondary Treatment	1976
Cumberland Farms; Westboro, MA	0.015	Secondary Treatment	1976
Warren County Vocational School; Lebanon, OH	0.025	Secondary Treatment	1977
River West Estates; Casper, WY	0.040	Secondary Treatment	1977
Lake Meade, PA	0.056	Secondary Treatment	1977
Fort Columbia, OR	0.005	Secondary Treatment	1977
Suffolk County Community College, Long Island, NY	0.035	Secondary Treatment	1977
Hydaburg, AK	0.090	Secondary Treatment	1978
Monmouth Battlefield; Freehold, NJ	0.035	Secondary Treatment	1978
Willow Wood Condominiums; Yarmouth, MA	0.030	Secondary Treatment	1978
Craig, AK	0.071	Secondary Treatment	1978
Klawock, AK	0.050	Secondary Treatment	1978
Fresh Water Bay, AK	0.005	Secondary Treatment	1978
Downsville, WI	0.030	Secondary Treatment	1978
Buck Island Village; West Yarmouth, MA	0.030	Secondary Treatment	1978
Bridgewater, VT	0.043	Secondary Treatment	1978

APPENDIX A
(continued)

(A) Manufacturer: Autotrol (continued) - Package Plants

Plant	Design flow mgd	Treatment	Date of start-up
S. Koochiching School District 363; Indus, MN	0.007	Secondary Treatment	1979
Wrangell, AK	0.005	Secondary Treatment	1979
Galla, AK	0.002	Secondary Treatment	1979
Crab Bay, AK	0.005	Secondary Treatment	1979
Corner Bay, AK	0.009	Secondary Treatment	1979
Keoka Bay, AK	0.001	Secondary Treatment	1979
Tyler Brothers	0.009	Secondary Treatment	1979
Mud Bay, AK	0.015	Secondary Treatment	1979
Angoon, AK	0.058	Secondary Treatment	1979
Duquesne Light Company; Shipping Port, PA	0.022	Secondary Treatment	1979
Way Family Ranch; Gunnison, CO	0.020	Secondary Treatment	1979
Saginaw Bay, AK	0.005	Secondary Treatment	1980

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APPENDIX A
(continued)

(B) Manufacturer: Clow-Envirodisc

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
Hyde Park Nursing Home	0.018	Secondary Treatment and Nitrification	1	1973
Hyde Park Hights Apts.	0.029	Secondary Treatment and Nitrification	1	1973
Town of Wappingers Sewer District	0.212	Secondary Treatment and Nitrification	2	1975
Hidden Hollow Apts.	0.031	Secondary Treatment and Nitrification	1	1974
Greenfields East	0.157	Secondary Treatment and Nitrification	2	1980
Valley Dale	0.048	Secondary Treatment and Nitrification	1	1974
Mahopac Plaza	0.014	Secondary Treatment and Nitrification	1	1975
B.G.B. Mobile Homes	0.025	Secondary Treatment and Nitrification	1	1973
Golden & Golden Apts.	0.015	Secondary Treatment and Nitrification	1	1974
Washington Township, NJ	0.300	Secondary Treatment and Nitrification	3	1976
Wingdale School	0.008	Secondary Treatment and Nitrification	1	1975
Pope Pius XII Campus	0.012	Secondary Treatment	1	1975
Aloha Home Acres	0.035	Secondary Treatment and Nitrification	1	1979
Huntington, CA	0.044	Secondary Treatment	1	1979
Cott Corporation	0.086	Secondary Treatment and Nitrification	4	1978
Somers, NY	0.060	Secondary Treatment and Nitrification	1	1978
Baldwin Place Shopping Center	0.027	Secondary Treatment and Nitrification	1	1978
Chateau Hyde Park	0.020	Secondary Treatment and Nitrification	1	1977
Rhinebeck Baptist Nursing Home	0.030	Secondary Treatment and Nitrification	1	1978
The Hansen Project	0.008	Secondary Treatment	1	1976

APPENDIX A
(continued)

(B) Manufacturer: Clow-Envirodisc

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
Voorhees Township, NJ	1.170	Secondary Treatment	6	1978
Plainville, CT	3.200	Secondary Treatment and Nitrification	24	1978
International Falls, MN	N/A	Secondary Treatment	1	1977
Ellsworth, ME	0.650	Secondary Treatment	5	1978
Chautauqua, NY	0.840	Secondary Treatment and Nitrification	2	1978
Webster City, IA	2.300	Secondary Treatment and Nitrification	20	1978
Mt. Olive, NC	0.675	Secondary Treatment and Nitrification	4	1978
Black Creek, WI	0.335	Secondary Treatment and Nitrification	12	1978
Grand Union	0.004	Secondary Treatment and Nitrification	1	1978
Town of Hanover, NY	0.500	Secondary Treatment	3	1978
No. Little Rock, AR	12.000	Secondary Treatment	32	1978
Greenfields; Hyde Park, NY	0.150	Secondary Treatment and Nitrification	2	1978
Delafield Hartland, WI	2.530	Secondary Treatment and Nitrification	16	1978
Ft. Walton Beach, FL	4.500	Secondary Treatment	20	1978
Lower Little Miami, OH	2.200	Secondary Treatment and Nitrification	10	1978
Effingham, IL	2.500	Secondary Treatment and Nitrification	24	1978
Holly, MI	1.200	Secondary Treatment and Nitrification	12	1978
Rio Dell, CA	0.338	Secondary Treatment	3	1978
Clarke County, OH	2.000	Secondary Treatment and Nitrification	15	1978
Yaphank County Center, NY	0.250	Secondary Treatment and Nitrification	8	1978

APPENDIX A
(continued)

(C) Manufacturer: Tait Bio Shafts, Inc.

Plant	Design flow mgd	Treatment	No. of shafts	Date of start-up
Kerr-McGee Chemical Company	0.025	Secondary Treatment	1	1977
Lincolnway School	0.065	Secondary Treatment	1	1977
Purestream Ind.	0.220	Secondary Treatment and Nitrification	1	1977
Warrenton, Town of	1.000	Secondary Treatment	4	1977
Liquid Carbonics Corporation	0.004	Secondary Treatment	1	1977
Langdale Ferry	0.025	Secondary Treatment	1	1978
Nickerson Farms	0.002	Secondary Treatment	1	1978
Dover, Town of	0.500	Secondary Treatment and Nitrification	2	1978
Bellville, City of	0.600	Secondary Treatment	2	1978
Crescent City	3.500	Secondary Treatment	12	1979
Union Grove, City of	0.750	Secondary Treatment and Nitrification	3	1978
Liquid Carbonics Corporation	0.002	Secondary Treatment	10	1979
Hartvard, City of	1.500	Secondary Treatment and Nitrification	10	1979
Carmel, Town of	0.500	Secondary Treatment	3	1979
Thetford Corporation		Secondary Treatment	1	1979
Blackberry Hills	0.063	Secondary Treatment		1979
International Fabco	0.100	Secondary Treatment	2	1979
Garthright	0.018	Secondary Treatment		1979

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(continued)

(D) Manufacturer: Hormel Corporation

Plant	Design flow mgd
Austin, MI	2.65
Cascade, IA	0.22
Converse, IN	0.25
DeKalb, IL	7.25
Eagle, NE	0.12
Harlan, IA	0.72
Marion, IL	2.50
Marissa, IL	N/A
Monroe, NC	8.00
Morton, IL	3.00
Mt. Morris, IL	N/A
Nebraska City, NB	2.55
Talbot County, MD	0.50
Valentine, NB	0.35
Wood River, NB	0.23
Ionia, MI	2.80

APPENDIX B

CALCULATION AND LISTING OF MONTHLY AVERAGE BOD REMOVAL EFFICIENCIES AND MONTHLY AVERAGE EFFLUENT CONCENTRATION

METHOD OF ANALYSIS

1. Monthly Average Parameters were computed as:

$$\overline{X} = \text{ANTILOG} \left[\frac{\sum_{i=1}^{N} X_{Li}}{N} \right]$$

Where

$\overline{X}$ = monthly average value

X_L = log value of monthly data

N = number of data points

The value of $\overline{X}$ per plant is reported in Table 11 as Monthly Average BOD Removal Efficiency and Monthly Average Effluent Concentration.

2. Standard deviations were computed as:

$$S = \sqrt{\frac{(X_{Li} - \overline{X}_L)^2}{(N-1)}}$$

$$+ \sigma = \text{ANTILOG } [\overline{X}_L + S]$$

$$- \sigma = \text{ANTILOG } (\overline{X}_L - S)$$

Where

$\overline{X}_L$ = average log value = $\left[\frac{\sum_{i=1}^{N} X_{Li}}{N} \right]$

S = log sample standard deviation

PLANT ID. NO. 1

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
July	78	88.4	5.4	13.3	4.7
Aug	78	89.3	6.1	13.6	5.3
Sept	78	89.6	5.5	16.4	6.2
Oct	78	88.3	3.9	17.6	5.0
Nov	78	85.7	6.6	17.0	7.5
Dec	78	87.5	6.0	13.5	5.5
Jan	79	88.1	3.8	17.3	6.1
Feb	79	87.1	10.6	14.4	5.4
March	79	87.9	4.7	14.6	4.7
July	79	91.7	3.0	11.6	4.8

Mean BOD Removal Efficiency, percent = 88.34

Standard Deviation = 86.76 to 89.96

Mean Effluent Concentration, mg/L = 14.80

Standard Deviation = 12.89 to 16.97

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

PLANT ID. NO. 2

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
Aug	78	88.0	2.8	13.5	4.9
Oct	78	46.0	35.3	70.8	33.6
Nov	78	79.3	15.3	25.8	17.0
Dec	78	97.0	1.4	2.6	1.3
Jan	79	88.0	15.6	6.4	2.3
Feb	79	96.0	1.0	5.8	0.8
March	79	96.0	2.6	5.3	3.2
April	79	77.0	18.4	29.5	27.5
May	79	95.5	1.3	8.5	3.6
June	79	96.8	2.6	5.6	3.0
July	79	90.5	0.7	8.2	1.1
Aug	79	94.3	5.3	5.9	4.5
Sept	79	95.3	1.9	4.5	1.7

Mean BOD Removal Efficiency, percent = 86.25

Standard Deviation = 70.38 to 100 (105.7)[1]

Mean Effluent Concentration, mg/L = 9.29

Standard Deviation = 3.7 to 23.1

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

[1] 100 percent is maximum percent removal.

PLANT ID. NO. 3

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
Sept	78	77.3	9.6	35.5	19.8
Oct	78	86.0	---[1]	36.0	---[1]
Nov	78	77.5	9.7	26.5	9.9
Dec	78	68.3	3.5	32.3	7.2
Jan	79	66.3	12.6	36.3	12.8
March	79	64.3	21.0	21.8	10.3
April	79	56.5	10.3	46.3	17.3
May	79	65.3	20.0	27.8	12.6
June	79	88.5	3.6	14.2	4.9
July	79	87.0	1.8	18.3	5.4
Aug	79	86.2	8.7	13.0	6.0

Mean BOD Removal Efficiency, percent = 74.05

Standard Deviation = 63.53 to 86.32

Mean Effluent Concentration, mg/L = 26.06

Standard Deviation = 17.26 to 39.35

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

[1] Only monthly averages are reported. Sufficient data sample not available to compute standard deviation.

PLANT ID. NO. 4

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
Jan	78	83.0	6.5	12.5	3.0
Feb	78	86.0	4.4	10.7	2.1
March	78	76.0	14.3	13.0	5.5
April	78	88.0	5.7	10.8	2.2
May	78	75.0	15.4	11.0	1.7
June	78	70.3	29.0	25.0	23.0
July	78	91.8	5.4	9.8	5.7
Aug	78	88.6	3.8	11.4	3.9
Sept	78	97.5	2.1	3.0	1.4
Oct	78	96.0	1.4	4.0	1.4
Nov	78	89.6	12.0	12.2	5.8
Dec	78	85.7	4.0	10.3	2.3

Mean BOD Removal Efficiency, percent = 84.83

Standard Deviation = 77.17 to 93.25

Mean Effluent Concentration, mg/L = 9.88

Standard Deviation = 5.84 to 16.73

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

PLANT ID. NO. 5

Date		Monthly average BOD removal efficiencies	Standard deviation[1]	Monthly average effluent concentration mg/L	Standard deviation[1]
Month	Year				
Jan	76	81	---	24	---
April	76	88	---	28	---
May	76	85	---	27	---
June	76	91	---	26	---
July	76	90	---	33	---
Aug	76	87	---	39	---
Oct	76	90	---	39	---
Nov	76	93	---	21	---
Dec	76	89	---	33	---
Jan	77	88	---	28	---
Feb	77	85	---	30	---

Mean BOD Removal Efficiency, percent = 87.85

Standard Deviation = 84.55 to 91.28

Mean Effluent Concentration, mg/L = 28.96

Standard Deviation = 24.30 to 34.51

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

[1] Only monthly averages are reported. Sufficient data sample not available to compute standard deviation.

PLANT ID. NO. 6

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
Jan	78	89.	---[1]	12.2	---[1]
April	78	93.	---[1]	12.	---[1]
Aug	78	88.	---[1]	16.	---[1]
Sept	78	88.	---[1]	17.	---[1]
Feb	80	96.8	3.3	6.6	4.4
March	80	93.0	7.1	6.6	4.4
April	80	89.7	5.9	8.3	2.9

Mean BOD Removal Efficiency, percent = 91.02

Standard Deviation = 87.82 to 94.34

Mean Effluent Concentration, mg/L = 10.53

Standard Deviation = 7.10 to 15.64

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

[1] Only monthly averages are reported. Sufficient data sample not available to compute standard deviation.

PLANT ID. NO. 7

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
Jan	79	91.0	1.4	20.5	7.8
Feb	79	76.8	18.5	37.8	16.2
March	79	93.3	2.1	15.3	6.0
April	79	87.3	11.1	24.0	27.2
May	79	89.4	2.5	26.0	8.7
June	79	91.0	1.7	23.0	1.7
July	79	84.5	9.7	32.0	18.3
Aug	79	87.4	3.6	19.6	14.3

Mean BOD Removal Efficiency, percent = 87.45

Standard Deviation = 82.29 to 92.93

Mean Effluent Concentration, mg/L = 23.92

Standard Deviation = 17.99 to 31.77

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

PLANT ID. NO. 8

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
March	78	69.7	7.3	27.6	7.6
May	78	73.9	6.1	22.2	5.1
Aug	78	78.8	5.5	12.7	4.8
Sept	78	78.6	5.6	13.8	3.1
Oct	78	73.2	7.4	16.6	3.6
Nov	78	79.9	4.2	14.6	5.3
Dec	78	77.0	6.5	19.3	6.4
Jan	79	78.9	6.3	15.7	5.5
Feb	79	74.7	2.5	17.8	1.8
March	79	61.6	18.1	23.7	10.2
April	79	46.6	16.4	29.8	7.5
May	79	58.4	10.9	27.1	4.5
June	79	57.2	12.4	23.0	5.1
July	79	50.4	16.5	25.9	6.6

Mean BOD Removal Efficiency, percent = 67.52

Standard Deviation = 56.38 to 80.86

Mean Effluent Concentration, mg/L = 19.97

Standard Deviation = 15.06 to 26.57

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

PLANT ID. NO. 9

Date		Monthly average BOD removal efficiencies	Standard deviation[1]	Monthly average effluent concentration mg/L	Standard deviation[1]
Month	Year				
July	78	75	---	41	---
Aug	78	81	---	26	---
Sept	78	84	---	24	---
Oct	78	87	---	32	---
Nov	78	90	---	25	---
Dec	78	88	---	17	---
Jan	79	76	---	47	---
Feb	79	66	---	45	---
March	79	69	---	33	---
April	79	82	---	14	---
May	79	76	---	21	---
June	79	84	---	15	---
July	79	86	---	11	---

Mean BOD Removal Efficiency, percent = 79.97

Standard Deviation = 72.71 to 87.98

Mean Effluent Concentration, mg/L = 24.55

Standard Deviation = 15.45 to 39.02

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

[1] Only monthly averages are reported. Sufficient data sample not available to compute standard deviation.

PLANT ID. NO. 10

Date		Monthly average BOD removal efficiencies	Standard deviation[1]	Monthly average effluent concentration mg/L	Standard deviation[1]
Month	Year				
July	75	91	---	20	---
Aug	75	90	---	18	---
Sept	75	89	---	23	---
Oct	75	89	---	25	---
Nov	75	85	---	28	---
Dec	75	83	---	44	---
Jan	76	83	---	37	---
Feb	76	88	---	31	---
March	76	88	---	30	---
April	76	91	---	20	---
May	76	88	---	33	---
June	76	89	---	27	---

Mean BOD Removal Efficiency, percent = 87.79

Standard Deviation = 85.05 to 90.63

Mean Effluent Concentration, mg/L = 27.09

Standard Deviation = 20.74 to 35.39

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

[1] Only monthly averages are reported. Sufficient data sample not available to compute standard deviation.

PLANT ID. NO. 11

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
Oct	78	63.2	17.8	89.8	48.8
Nov	78	78.3	5.2	29.5	7.3
Dec	78	76.1	7.8	31.3	4.5
April	79	78.5	10.0	23.8	9.2
May	79	77.5	1.0	29.0	1.4
June	79	80.3	6.5	23.7	3.1
July	79	66.7	35.0	22.0	4.2
Aug	79	78.5	9.6	22.2	6.1
Sept	79	81.7	7.6	35.0	13.5
Oct	79	86.9	6.3	24.6	12.8
Nov	79	87.6	5.0		

Mean BOD Removal Efficiency, percent = 77.42

Standard Deviation = 70.16 to 85.44

Mean Effluent Concentration, mg/L = 29.42

Standard Deviation = 19.97 to 45.92

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

PLANT ID. NO. 12

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
Sept	78	77.8	9.9	27.7	24.9
Oct	78	90.8	4.1	24.8	5.8
Nov	78	89.5	4.6	28.4	11.9
Dec	78	81.2	2.9	30.0	6.5
Feb	79	85.4	4.4	30.7	10.1
March	79	82.9	6.3	24.6	12.4
April	79	78.3	13.0	32.2	22.6
May	79	71.1	21.3	34.8	11.3
June	79	79.6	12.6	32.1	10.9
July	79	87.8	2.8	19.9	8.6
Aug	79	87.4	6.2	18.9	8.1
Sept	79	82.3	8.8	22.8	8.5

Mean BOD Removal Efficiency, percent = 82.66

Standard Deviation = 77.06 to 88.66

Mean Effluent Concentration, mg/L = 26.78

Standard Deviation = 22.21 to 32.30

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

PLANT ID. NO. 13

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
Jan	78	96.9	1.7	5.2	2.0
Feb	78	96.5	3.4	5.7	2.9
March	78	90.5	3.5	12.5	3.5
April	78	87.5	3.0	11.7	5.2
May	78	89.8	5.0	8.2	3.7
June	78	94.0	4.7	6.1	2.8
July	78	92.0	5.2	8.0	3.0
Aug	78	96.1	3.2	6.6	3.5
Sept	78	95.1	4.0	5.9	2.4
Oct	78	96.8	1.8	4.8	1.7
Nov	78	97.2	1.0	4.3	1.1
Dec	78	95.6	3.9	7.0	3.7
Jan	79	89.9	3.1	10.1	4.8
Feb	79	89.1	3.4	12.7	2.8
April	79	77.6	6.8	16.0	1.6
May	79	69.8	6.4	13.9	2.9
June	79	76.2	11.1	13.0	3.2
July	79	82.2	9.1	12.0	3.4

Mean BOD Removal Efficiency, percent = 88.90

Standard Deviation = 81.32 to 98.20

Mean Effluent Concentration, mg/L = 7.82

Standard Deviation = 6.20 to 12.79

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

PLANT ID. NO. 14

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	**Year**				
Nov	78	74.3	12.8	35.6	9.8
Dec	78	78.5	8.1	24.2	6.2
Jan	79	73.2	4.8	34.8	5.1
Feb	79	68.9	4.9	35.8	7.1
March	79	55.5	12.3	28.0	8.4
April	79	52.7	12.8	18.9	4.9
May	79	74.6	10.4	16.2	4.5
June	79	75.9	9.7	21.2	6.3
July	79	77.4	9.5	21.4	9.1
Aug	79	86.1	5.2	14.8	6.8
Sept	79	87.7	3.4	15.3	4.7

Mean BOD Removal Efficiency, percent = 72.36

Standard Deviation = 61.67 to 84.91

Mean Effluent Concentration, mg/L = 23.15

Standard Deviation = 15.85 to 31.60

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

PLANT ID. NO. 15

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
March	78	78.3	5.8	24.3	7.0
May	78	80.0	4.9	24.9	5.8
June	78	83.1	6.3	21.5	5.8
July	78	78.3	7.8	27.2	9.3
Aug	78	77.5	9.2	34.6	18.6
Sept	78	93.2	4.2	14.7	8.0
Oct	78	85.1	6.3	27.6	8.7
Nov	78	91.6	3.3	13.6	3.6
Jan	79	90.5	6.1	15.3	5.4
Feb	79	94.6	1.8	13.3	3.7
March	79	91.4	3.1	8.8	2.0
April	79	91.6	2.6	9.9	2.5
May	79	92.2	3.5	11.8	5.4
June	79	93.0	2.7	12.5	3.7
July	79	90.2	3.1	14.4	3.0
Aug	79	89.2	4.5	14.6	5.2

Mean BOD Removal Efficiency, percent = 87.28

Standard Deviation = 81.29 to 93.72

Mean Effluent Concentration, mg/L = 16.72

Standard Deviation = 11.18 to 25.00

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

PLANT ID. NO. 16

Date		Monthly average BOD removal efficiencies	Standard deviation	Monthly average effluent concentration mg/L	Standard deviation
Month	Year				
Feb	79	73.9	16.1	37.2	13.1
March	79	69.6	10.1	34.5	10.7
April	79	69.5	10.7	18.8	6.5
May	79	81.7	4.5	18.6	4.5
June	79	85.2	8.9	14.4	7.7

Mean BOD Removal Efficiency, percent = 75.71

Standard Deviation = 68.98 to 83.11

Mean Effluent Concentration, mg/L = 23.02

Standard Deviation = 15.15 to 34.98

The methods used to compute the preceding means and standard deviations are described in the introduction to this appendix.

APPENDIX C

RESULTS OF REGRESSION ANALYSIS USING FIELD DATA FROM 16 PLANTS

	Percent BOD removal (Y) vs hydraulic loading (X)[1]				Organic removal (Y)[2] vs hydraulic loading (X)[1]				Organic removal (Y)[2]
Parameter	0-74[3]	75-124[3]	125-174[3]	175-350[3]	0-74[3]	75-124[3]	125-174[3]	175-350[3]	vs organic removal (X)[4]
Correlation	-0.52	-0.47	-0.51	-0.93	0.61	0.76	0.77	0.83	0.96
Slope	-6.77	-7.92	-0.75	-1.25	0.19	0.57	0.97	1.54	0.82
Y-Intercept	84.5	94.5	85.7	39.4	0.30	0.21	0.24	0.19	-0.06
Number of Data Points	99	105	82	52	99	105	82	52	211
Average X-Value	2.2	1.8	1.7	1.7	2.2	1.8	1.7	1.7	1.49
Standard Deviation X-Value	1.3	0.7	0.5	0.5	1.3	0.7	0.5	0.5	0.90
Average Y-Value	69.6	79.3	85.1	86.6	0.72	1.24	1.86	2.77	1.89
Standard Deviation Y-Value	17.0	14.0	9.6	8.7	0.39	0.53	0.72	1.03	1.05
95 Percent Confidence Limits	29.2	26.9	19.3	17.0	0.62	0.70	0.77	1.22	0.68
Average BOD Concentration, mg/L	52	97	143	214	52	97	148	214	114

[1] Units in gpd/sf of media.

[2] Units in lbs BOD removed/day/1,000 sf of media.

[3] Range of influent BOD concentration, mg/L.

[4] Units in lbs BOD applied/day/1,000 sf of media.

APPENDIX D

IDENTIFICATION OF SURVEY PLANTS

Plant ID No.	Location
1	Rhinelander, Wisconsin
2	Toppenish, Washington
3	Battleground, Washington
4	Wappingers Falls, New York
5	Edgewater, New Jersey
6	Washington Township, New Jersey
7	Selden, New York
8	Niagara, Wisconsin
9	Winchester, Kentucky
10	Gloucester, New Jersey
11	Thermopolis, Wyoming
12	North Huntington, Pennsylvania
13	Gladstone, Michigan
14	Cheboygan, Michigan
15	Ionia, Michigan
16	Hartford, Michigan
17	Voorhees Township, New Jersey
18	Bristol, Pennsylvania
19	Hamilton Township, New Jersey
20	Carmel, New York
21	Fennimore, Wisconsin
22	Lancaster, Wisconsin
23	Jonesville, Michigan
24	Dexter, Michigan
25	Indian Creek, Ohio
26	Honeoye, New York
27	Ellsworth, Maine
28	Pewaukee, Wisconsin
29	Alexandria, Virginia
30	Kirnsville, Missouri
31	Benton, Arkansas
32	Hopkington, Iowa
33	Ellsworth, Wisconsin
34	Fort Knox, Kentucky
35	Woodland, Washington
36	Georgetown, Kentucky
37	Valley, Maine

APPENDIX E

RBC DESIGN EXAMPLE USING INTERSTAGE DESIGN GUIDELINES

A. Influent Conditions: BOD_{IN} = 100 mg/L
FLOW = 1 mgd

B. Effluent Criteria: BOD_{OUT} = 15 mg/L

C. Assume SBOD:BOD = 0.5 for influent and effluent.

1. Determine total required surface area if system is one stage using interstage design guidelines.

1.1 SBOD = 0.5 (BOD) = 50 mg/L using the P and K_S values given in Table 28.

1.2 Calculate hydraulic loading from Equation 17:

$$HL_i = \frac{P_i S_i}{(K_i + S_i)(S_o - S_i)} = \frac{(1,000)(7.5)}{(161 + 7.5)(50 - 7.5)} = 1.05 \text{ gpd/sf}$$

or graphically determine HL_i from Figure 28.

1.3 Check for dissolved oxygen limitation. Calculate organic loading (O.L.): O.L. = HL_i x BOD x 0.00834 = 0.9 lbs/day/1,000 sf where,
BOD = 100 mg/L; HL_i = 1.05 gpd/sf or graphically determine whether loading is limiting from Figure 22.

1.4 Determine maximum required surface area.

$$SA = \frac{Q}{H.L.} = \frac{1 \text{ mgd}}{1.05 \text{ gpd/sf}} = 950,000 \text{ sf}$$

2. Determine number of stages for 85 percent removal. From Section 10, a minimum of three is recommended.

3. Determine the effect of staging on total required surface area.

   3.1 Divide total maximum required area evenly into three stages as follows:

   Stage 1: 317,000 sf
   Stage 2: 317,000 sf
   Stage 3: 317,000 sf

   3.2 Check for dissolved oxygen limitation by calculation or Figure 22.

   O.L. = 2.7 lbs BOD/day/1,000 sf; 2.7 lbs/day/1,000 sf $<$ 6.4 lbs/day/1,000 sf; loading O.K.

   3.3 Determine effluent concentration from interstage curve, Figure 28, or by using Equation 16.

$$S_i = \frac{[HL_i(S_o - K_i) - P_i] + \left([HL_i(S_o - K_i) - P_i]^2 + [4(HL_i)^2 (K_i)(S_o)]\right)^{1/2}}{2(HL_i)}$$

At 317,000 sf per stage, HL_i per stage

$$= \frac{1 \text{ mgd}}{317{,}000 \text{ sf}} = 3.15 \text{ gpd/sf}$$

For the first stage effluent concentration:

$$S_i = \frac{[3.15\ (50-161) - 1000] + \left([3.15\ (50-161) - 1000]^2 + [4(3.15)^2(161)(50)]\right)^{1/2}}{2(3.15)}$$

$$= 18$$

For the second stage effluent concentration:

$$S_i = \frac{[3.15\ (18-139) - 667] + \left([3.15\ (18-139) - 667]^2 + [4(3.15)^2(139)(18)]\right)^{1/2}}{2(3.15)}$$

$$= 7.4$$

Stage	Effluent concentration (SBOD)
1	18 mg/L
2	7.4 - effluent O.K.

3.4 Maximum total area with two stages = 317,000 x 2 = 634,000 sf.

3.5 Divide total two-staged area into three stages as follows:

Stage 1: 211,000
Stage 2: 211,000
Stage 3: 211,000

3.6 Check for dissolved oxygen limitation.

$$\text{New } HL_i = \frac{1 \text{ mgd}}{211{,}000 \text{ sf}} = 4.74 \text{ gpd/sf}$$

First stage O.L. = 4.0 lbs BOD/day/1,000 sf
4.0 lbs/day/1,000 sf $<$ 6.4 lbs/day/1,000 sf; loading O.K.

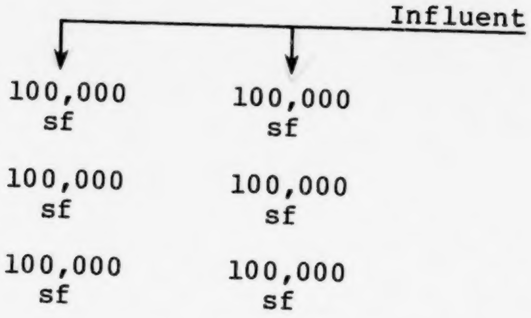
3.7 Determine effluent concentration per step 3.3.

Stage	Effluent concentration (SBOD)
1	23
2	12
3	6 - effluent O.K.

4. Select design.

4.1 Try six shafts at 100,000 sf/shaft.

Divide into two flow paths to ensure complete mix in each stage and to increase operational flexibility as follows:


Influent
100,000 sf
100,000 sf
100,000 sf
100,000 sf
100,000 sf
100,000 sf

4.2 Check dissolved oxygen limitation.

First stage O.L. = 4.2 lbs BOD/day/1,000 sf

4.3 Check effluent concentration.

Stage	Effluent concentration
1	24
2	13
3	7 - design O.K.

Note: If dissolved oxygen limitations were encountered in the design then first stage area would be determined by maximum allowable loading and same procedure would be followed (steps 1 to 4) to get from first stage effluent to the final effluent concentration.

APPENDIX F

COMPARISON OF FIELD DATA TO INTERSTAGE DESIGN PREDICTIONS

Organic removal[1] vs hydraulic loading[2]				Organic removal[1] vs organic loading[1]			
Influent conditions		Organic removal[1]		Influent conditions		Organic removal[1]	
RBC influent BOD concentration[3]	Hydraulic loading[2]	Actual[4]	Design[5]	RBC influent BOD concentration[3]	Organic loading[1]	Actual[4]	Design[5]
52	1	0.43	0.38	52	0.43	0.29	0.38
52	2	0.68	0.72	52	0.87	0.65	0.72
52	3	0.87	0.92	52	1.30	1.00	0.93
52	4	1.06	1.06	52	1.73	1.36	1.05
97	1	0.78	0.76	97	0.81	0.60	0.76
97	2	1.34	1.26	97	1.62	1.26	1.27
97	3	1.91	1.70	97	2.43	1.92	1.70
97	4	2.47	1.84	97	3.24	2.58	1.83
148	1	1.21	1.12	148	1.23	0.95	1.13
148	2	2.18	1.92	148	2.47	1.96	1.93
148	3	3.15	2.36	148	3.70	2.96	2.35
148	4	4.11	2.46	148	4.94	3.97	2.47
214	1	1.72	1.68	214	1.78	1.40	1.68
214	2	3.26	2.66	214	3.57	2.86	2.65
214	3	4.81	3.38	214	5.35	4.31	3.38
214	4	6.35	3.44	214	7.14	5.77	3.43

[1] Units: lbs BOD/day/1,000 sf.

[2] Units: gpd/sf.

[3] Units: mg/L.

[4] From linear regression of field data, Appendix C.

[5] Assumes BOD = 2 x SBOD.

TYPING GUIDE SHEET

APPENDIX G

EFFECTS OF STAGING ON SURFACE AREA REQUIREMENTS

Influent SBOD = 50 mg/L
Flow = 1.0 mgd

Design conditions		First stage		Second stage		Third stage		Fourth stage		
Minimum percent BOD removal	Effluent SBOD mg/L	Surface area sf	Reactor concentration mg/L	Surface area sf	Reactor concentration mg/L	Surface area sf	Reactor concentration mg/L	Surface area sf	Reactor concentration mg/L	Total surface area requirements
50	25	186,000	25.0	---	---	---	---	---	---	186,000
50	25	140,000	28.8	75,000	22.0	---	---	---	---	215,000
50	25	140,000	28.8	75,000	22.0	60,000	17.7	---	---	275,000
50	25	140,000	28.8	75,000	22.0	60,000	17.7	50,000	15.8	325,000
60	20	271,000	20.0	---	---	---	---	---	---	271,000
60	20	140,000	28.8	105,000	20.0	---	---	---	---	245,000
60	20	140,000	28.8	75,000	22.0	60,000	17.7	---	---	275,000
60	20	140,000	28.8	75,000	22.0	60,000	17.7	50,000	15.8	325,000
75	12.5	520,500	12.5	---	---	---	---	---	---	520,500
75	12.5	204,300	23.7	204,300	12.5	---	---	---	---	408,600
75	12.5	140,000	28.8	122,380	19.0	122,330	12.5	---	---	384,660
75	12.5	140,000	28.8	88,200	21.0	88,200	15.4	88,200	12.5	404,600
85	7.5	950,000	7.5	---	---	---	---	---	---	950,000
85	7.5	312,500	18.2	312,500	7.5	---	---	---	---	625,000
85	7.5	186,500	25.0	186,500	13.8	186,500	7.5	---	---	559,500
85	7.5	144,000	28.4	144,000	17.6	144,000	10.9	144,000	7.5	576,000
95	2.5	3,100,000	2.5	---	---	---	---	---	---	3,100,000
95	2.5	661,000	10.3	661,000	2.5	---	---	---	---	1,322,000
95	2.5	345,000	17.0	345,000	6.6	345,000	2.5	---	---	1,035,000
95	2.5	246,000	21.3	246,000	10.1	246,000	4.7	246,000	2.5	984,000